



U.S. DEPARTMENT OF
ENERGY

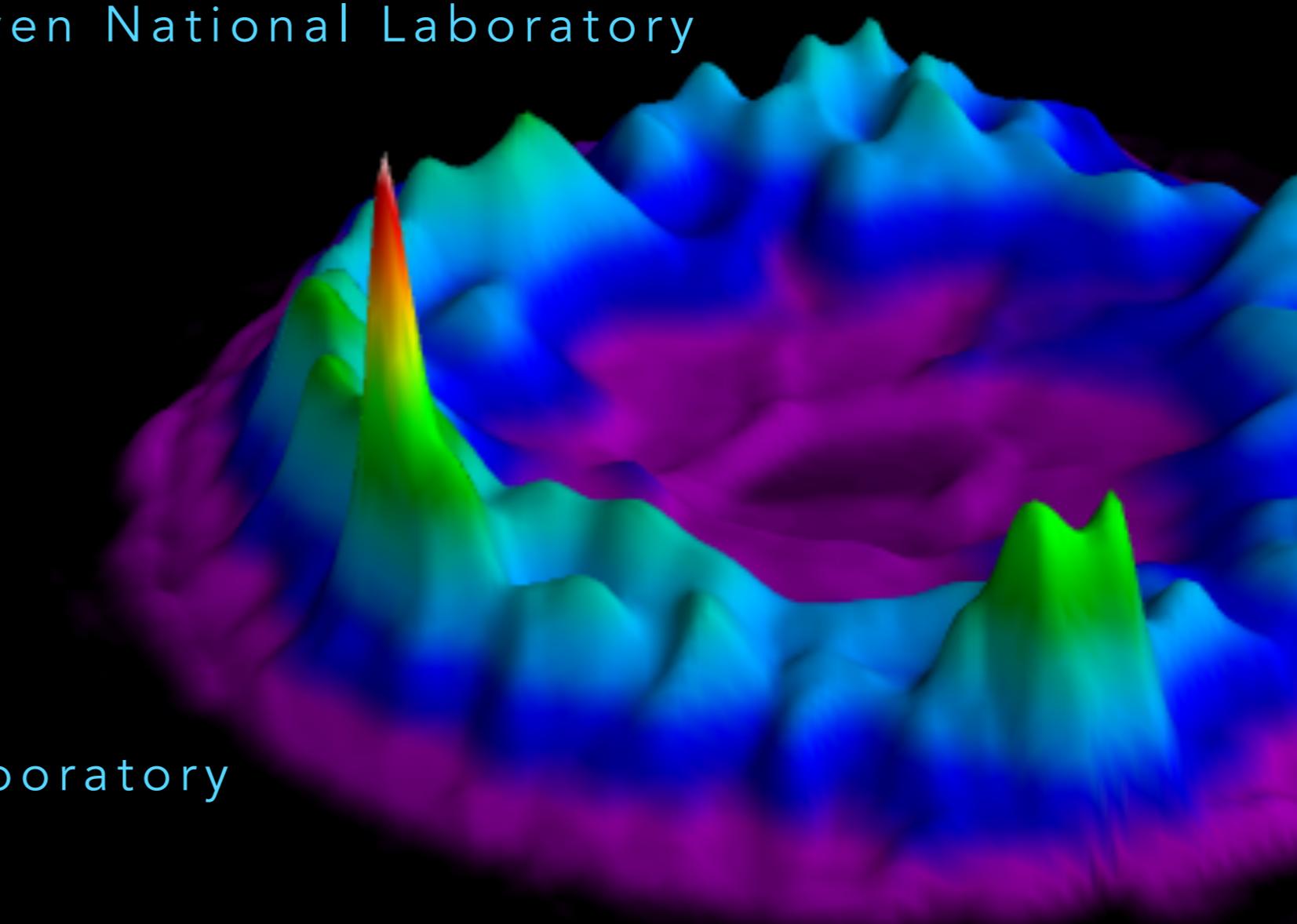
Office of
Science

BROOKHAVEN
NATIONAL LABORATORY

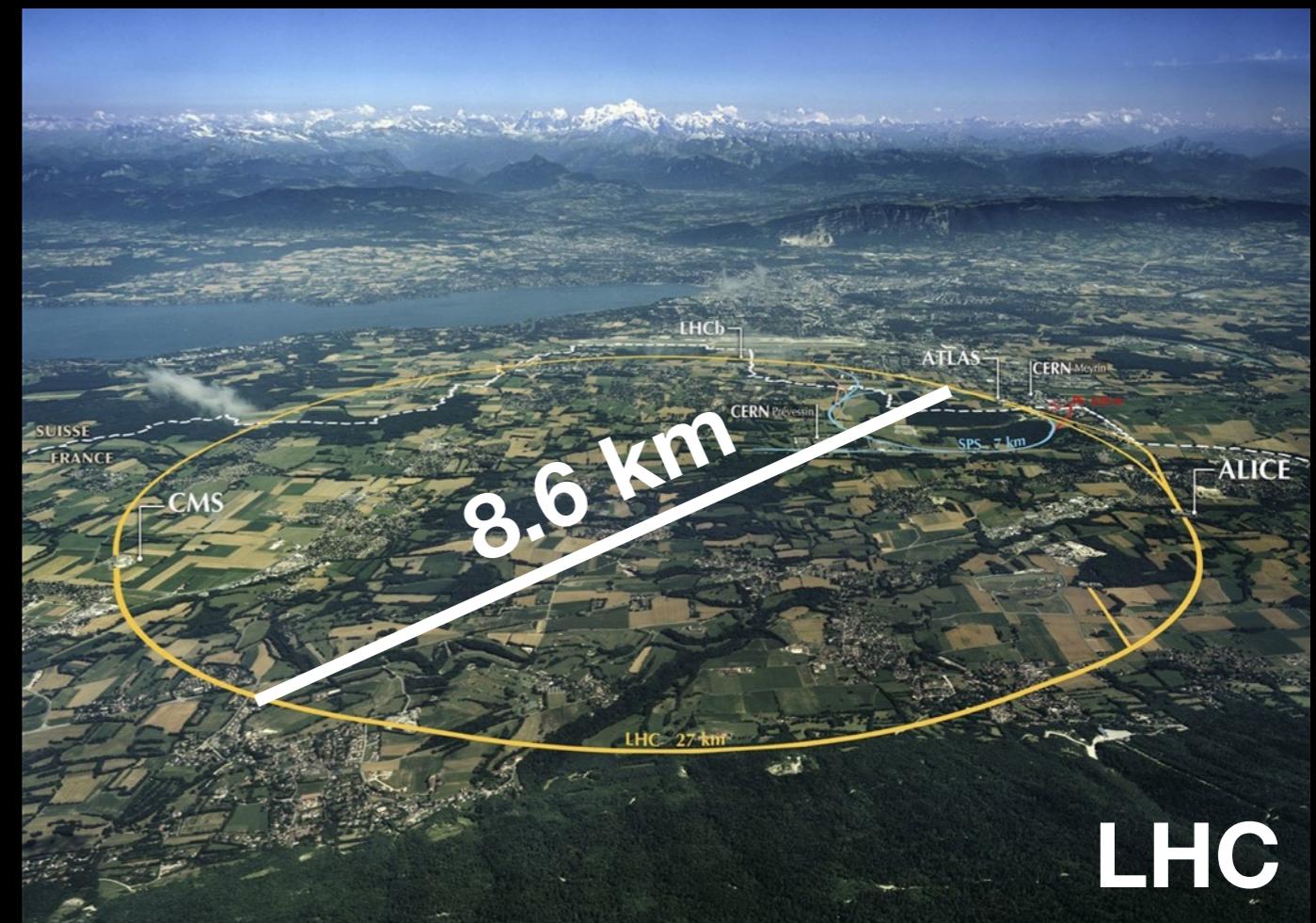
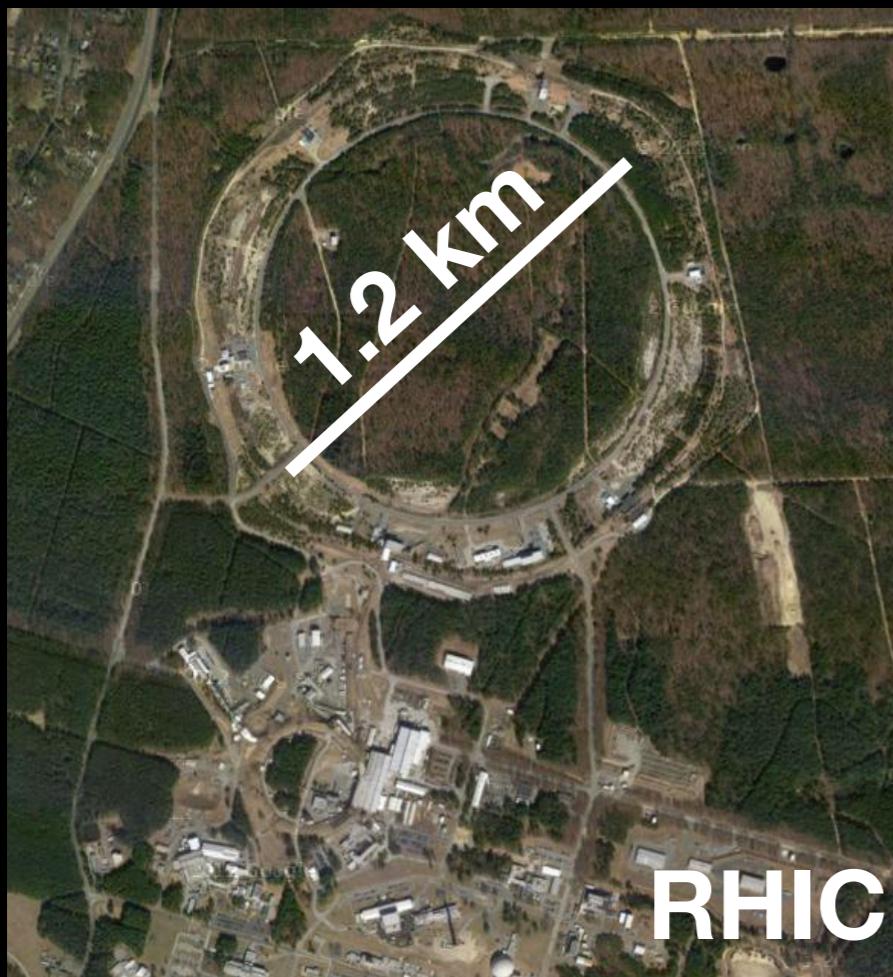
SNAPPING PICTURES OF THE PROTON WITH HEAVY IONS

Björn Schenke, Brookhaven National Laboratory

Physics Colloquium
Brookhaven National Laboratory
March 7 2017

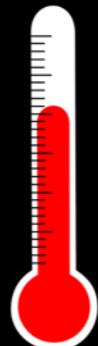


Heavy ion Collisions

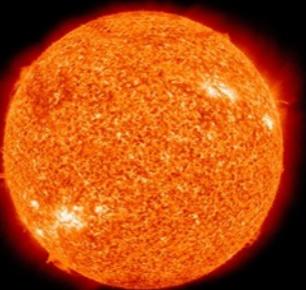


The stuff we create

Hot:



$>10^{12} \text{ K}$



100,000 times hotter than the sun or a hydrogen bomb (10^7 to 10^8 K)

Small:



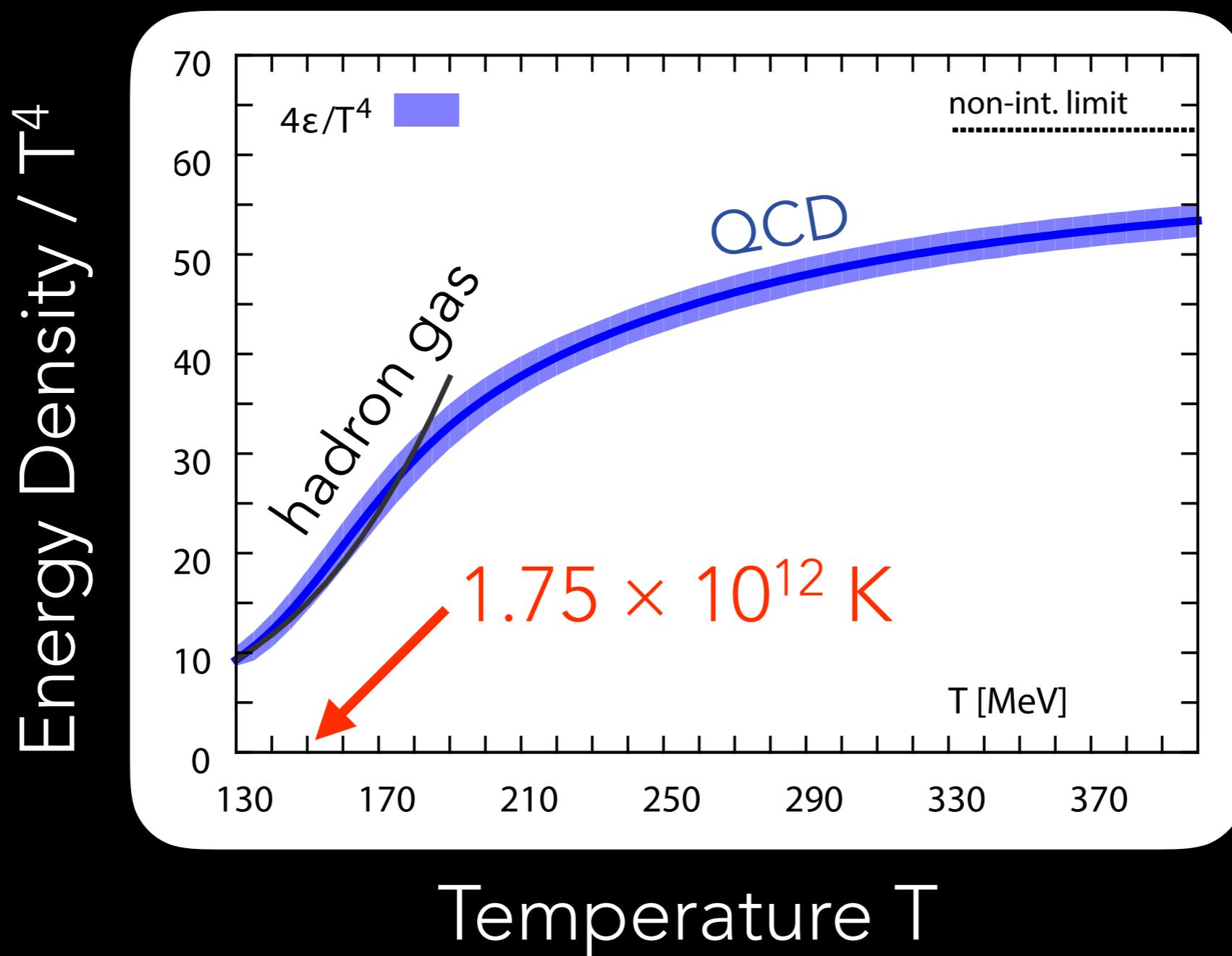
10^{-14} m



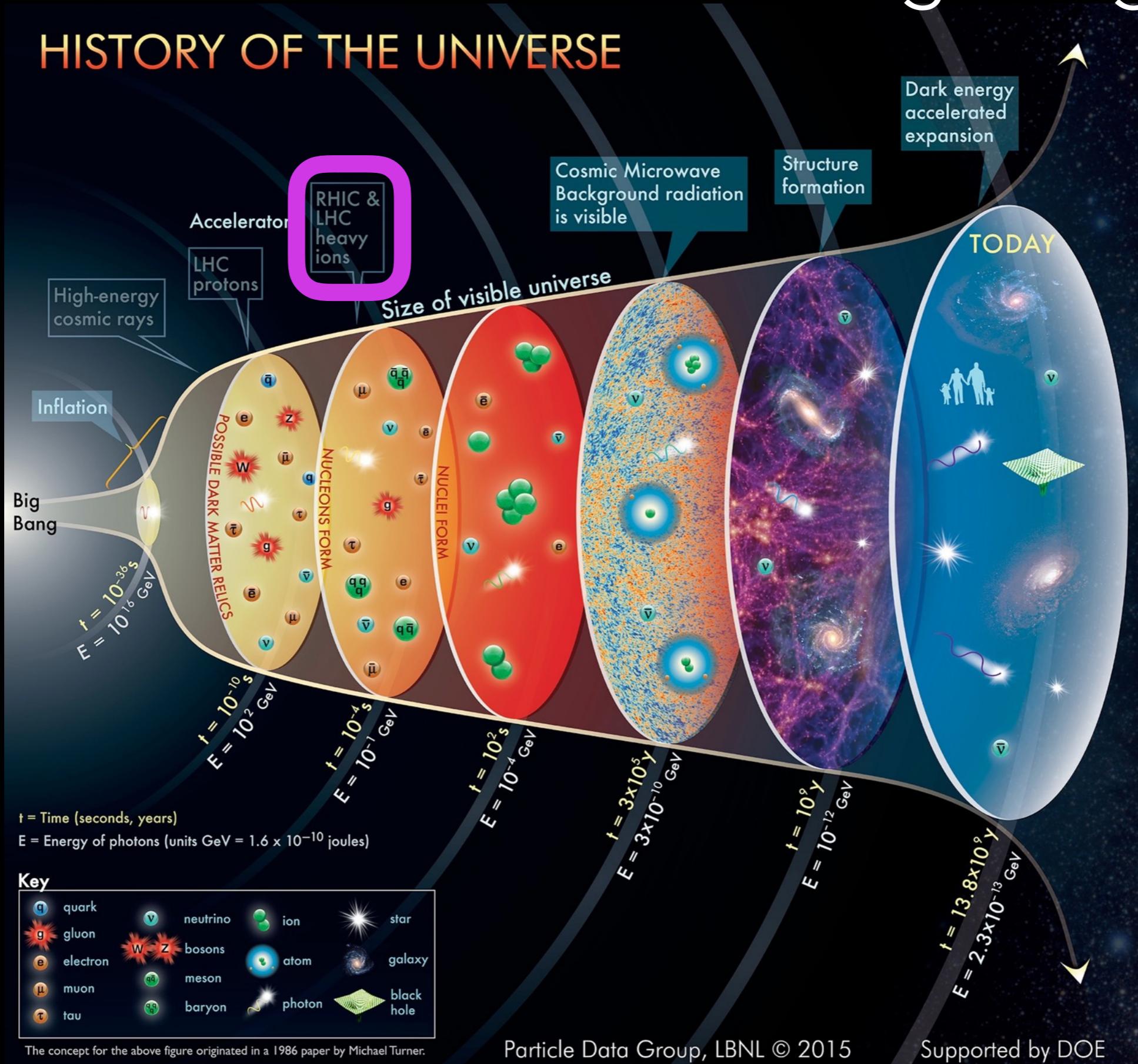
100,000,000,000 times smaller than a typical water droplet

Quark Gluon Plasma

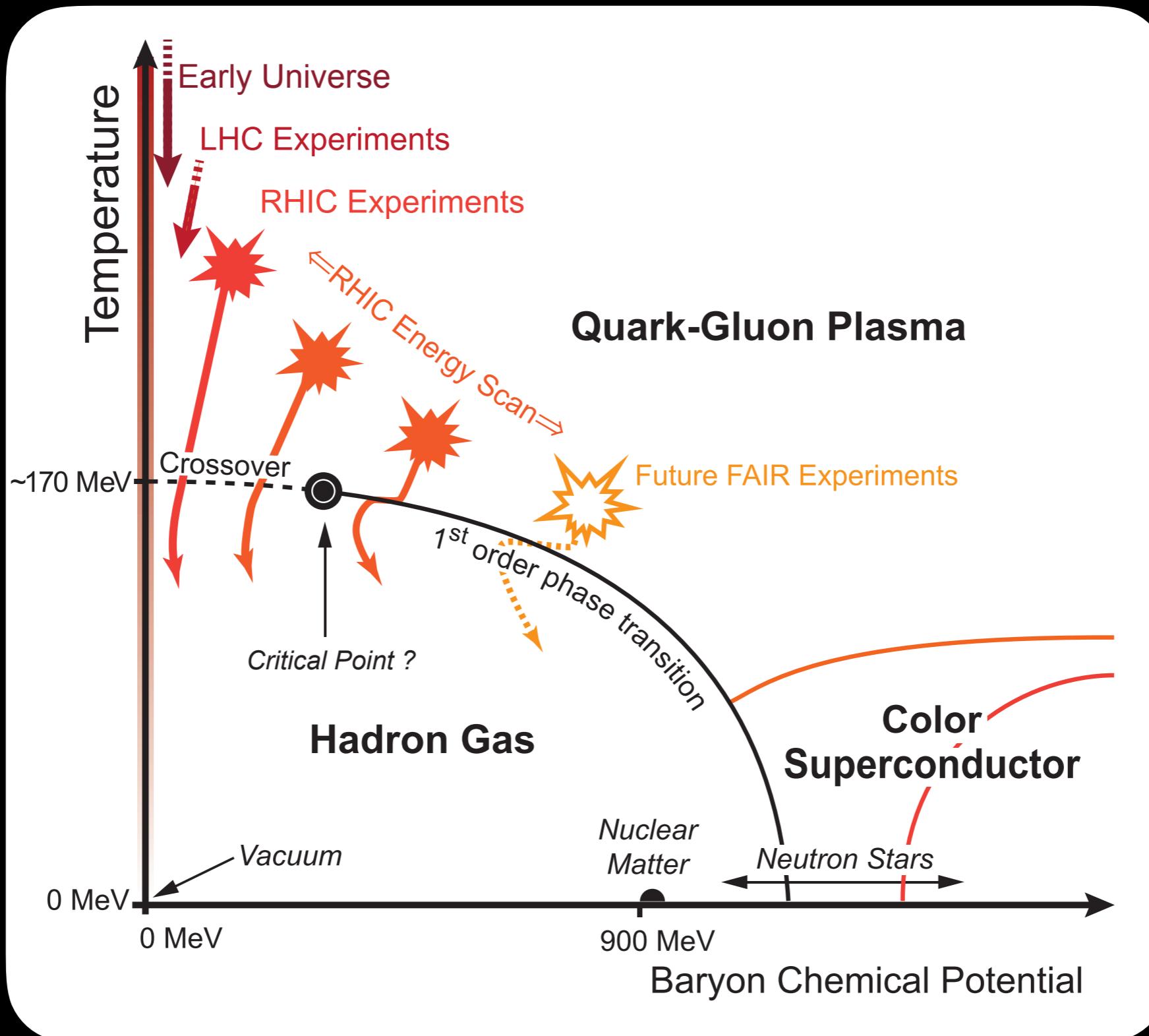
Quantum Chromodynamics (QCD) predicts crossover to system of liberated quarks and gluons at temperatures of $\sim 2 \times 10^{12}$ K



~10 microseconds after the big bang



Phase Diagram of hot QCD

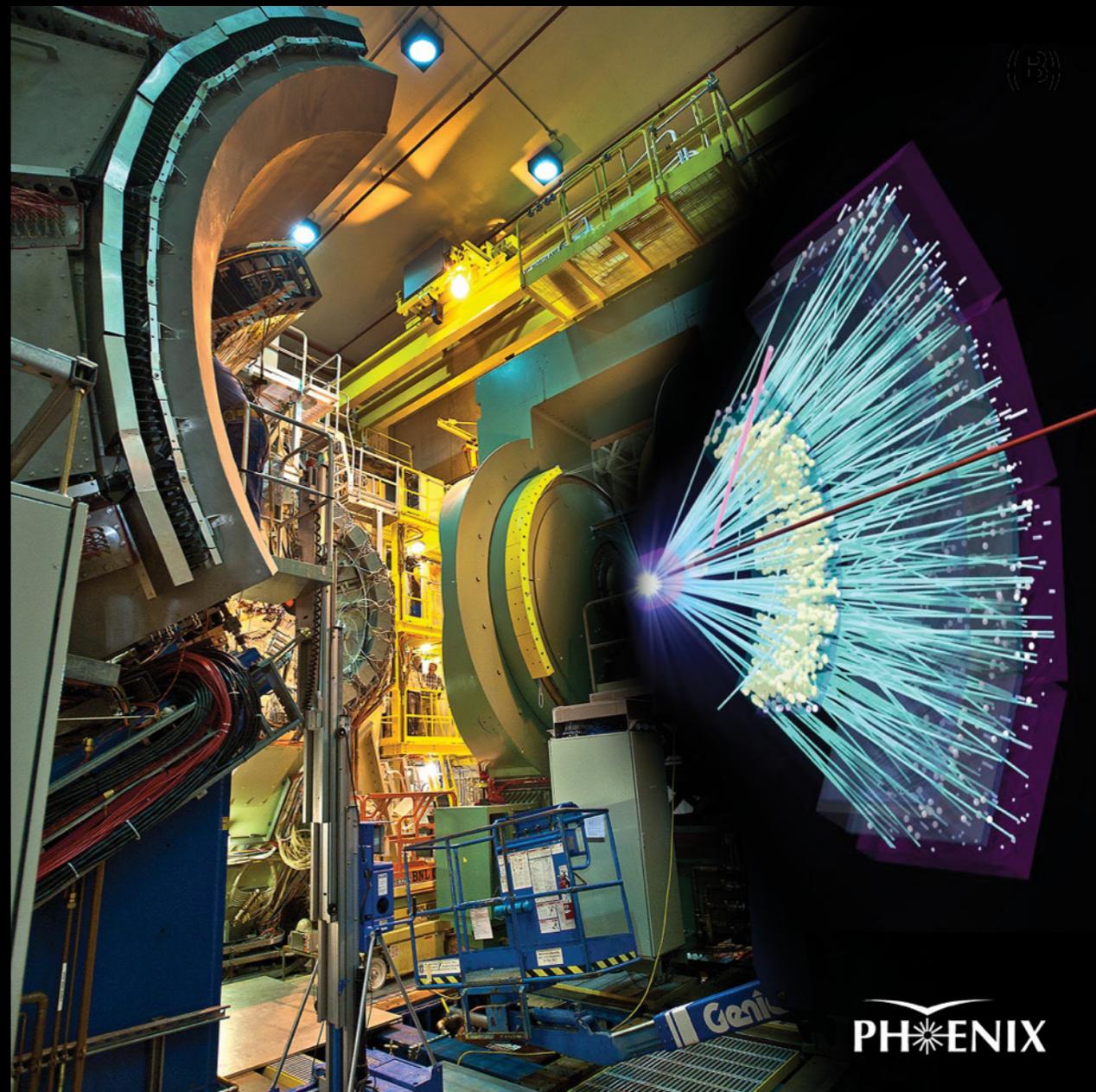
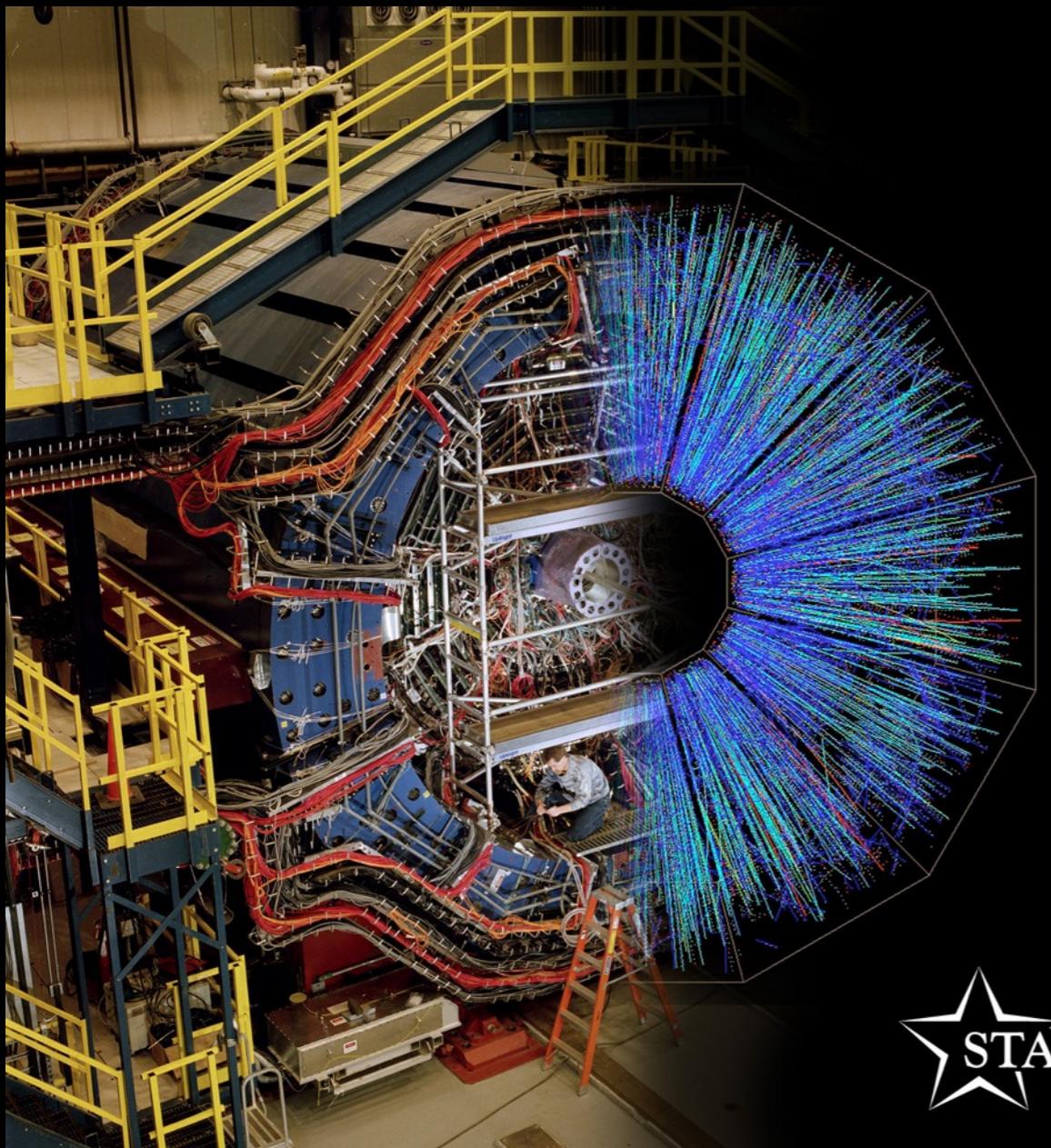


Perfect fluidity

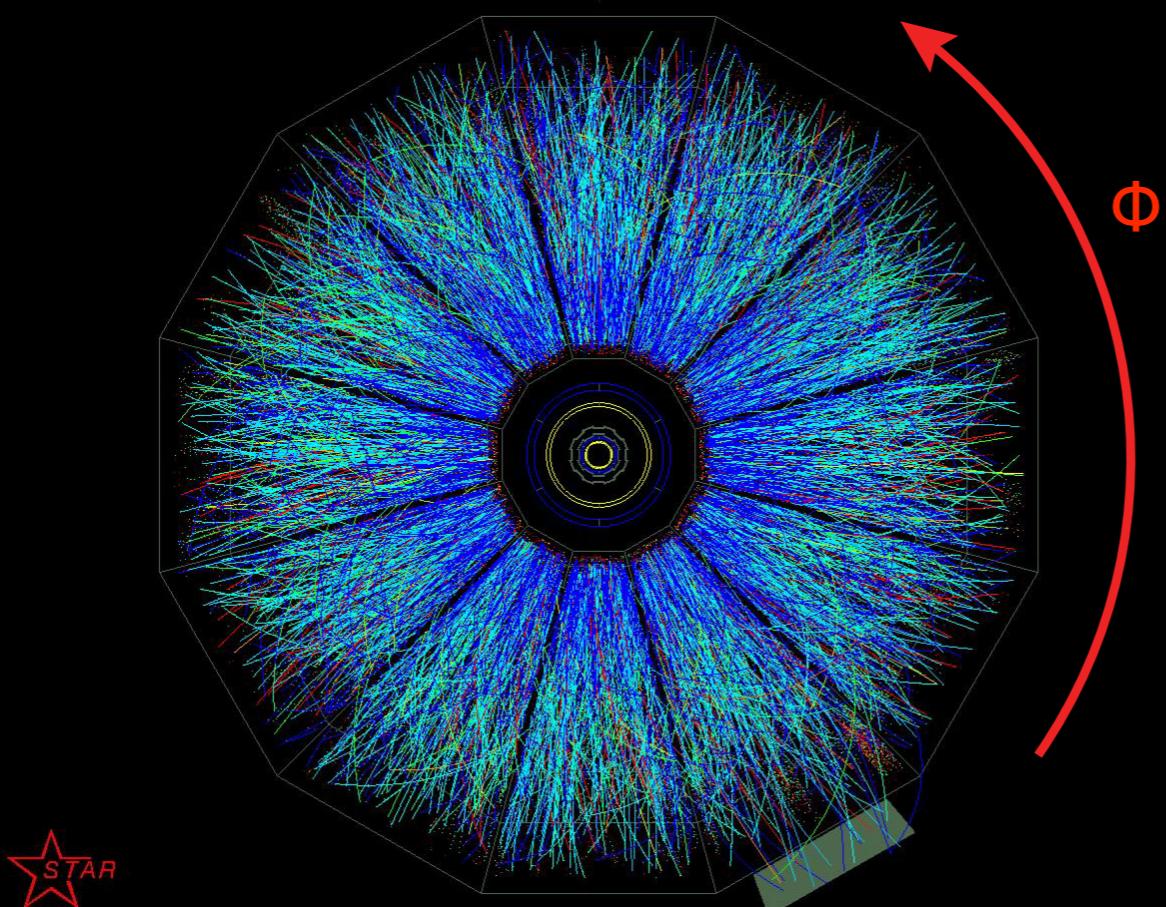
- **Discovery at RHIC:**
The Quark Gluon Plasma
behaves like an
almost perfect fluid
- confirmed by results
from LHC in 2010
- We conclude this from comparison
of measured azimuthal anisotropies in particle spectra
to theoretical calculations, in particular hydrodynamics



How we know this: Measure produced particles

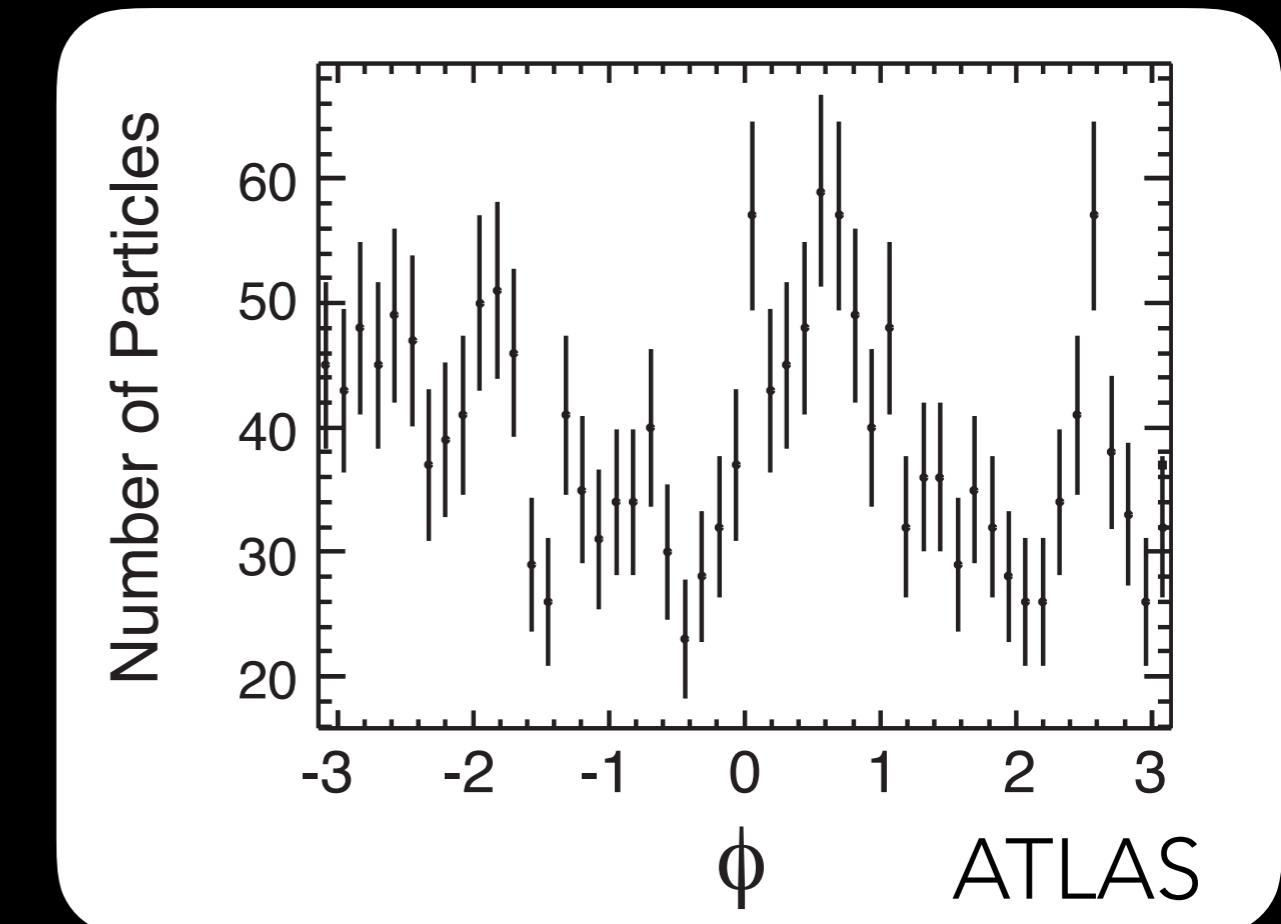
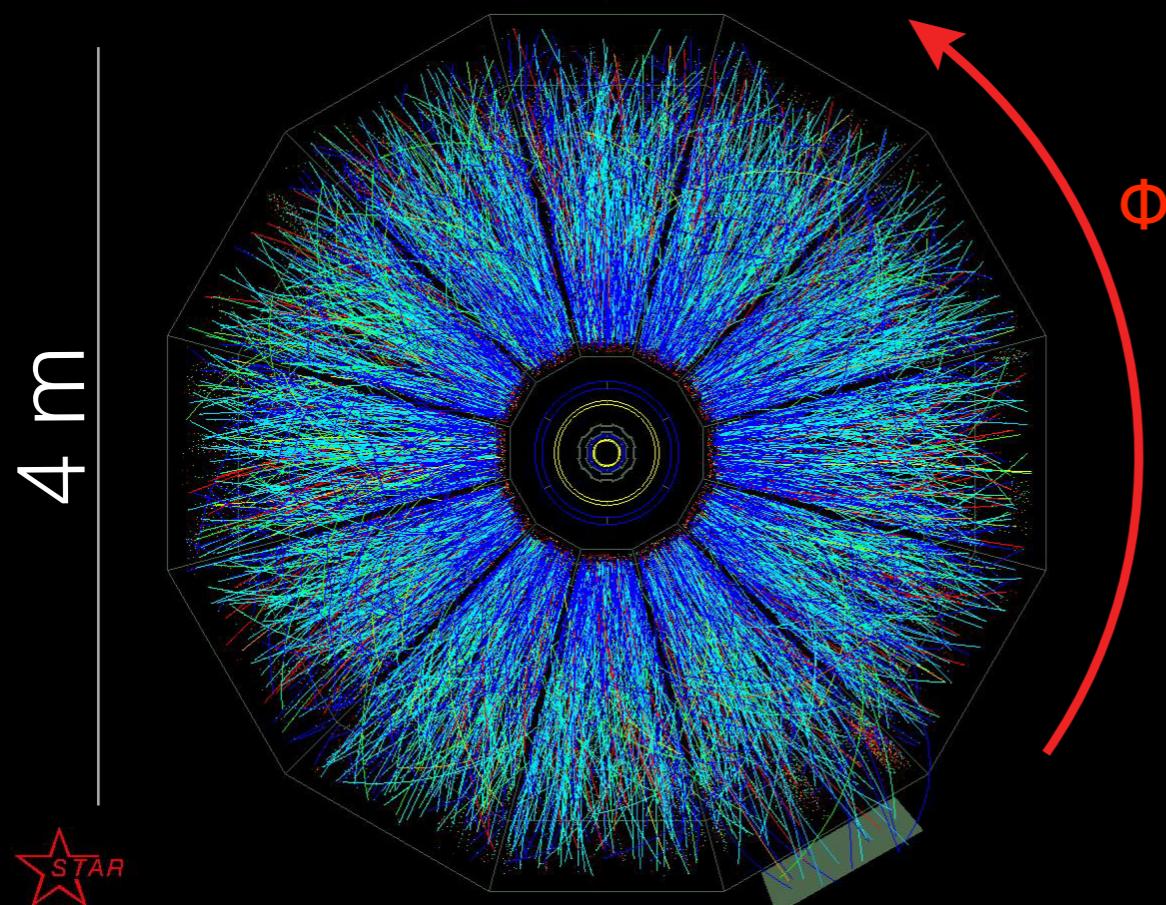


How we know this: Measure produced particles



Azimuthal anisotropies

Anisotropy of particle spectra transverse to the beam line

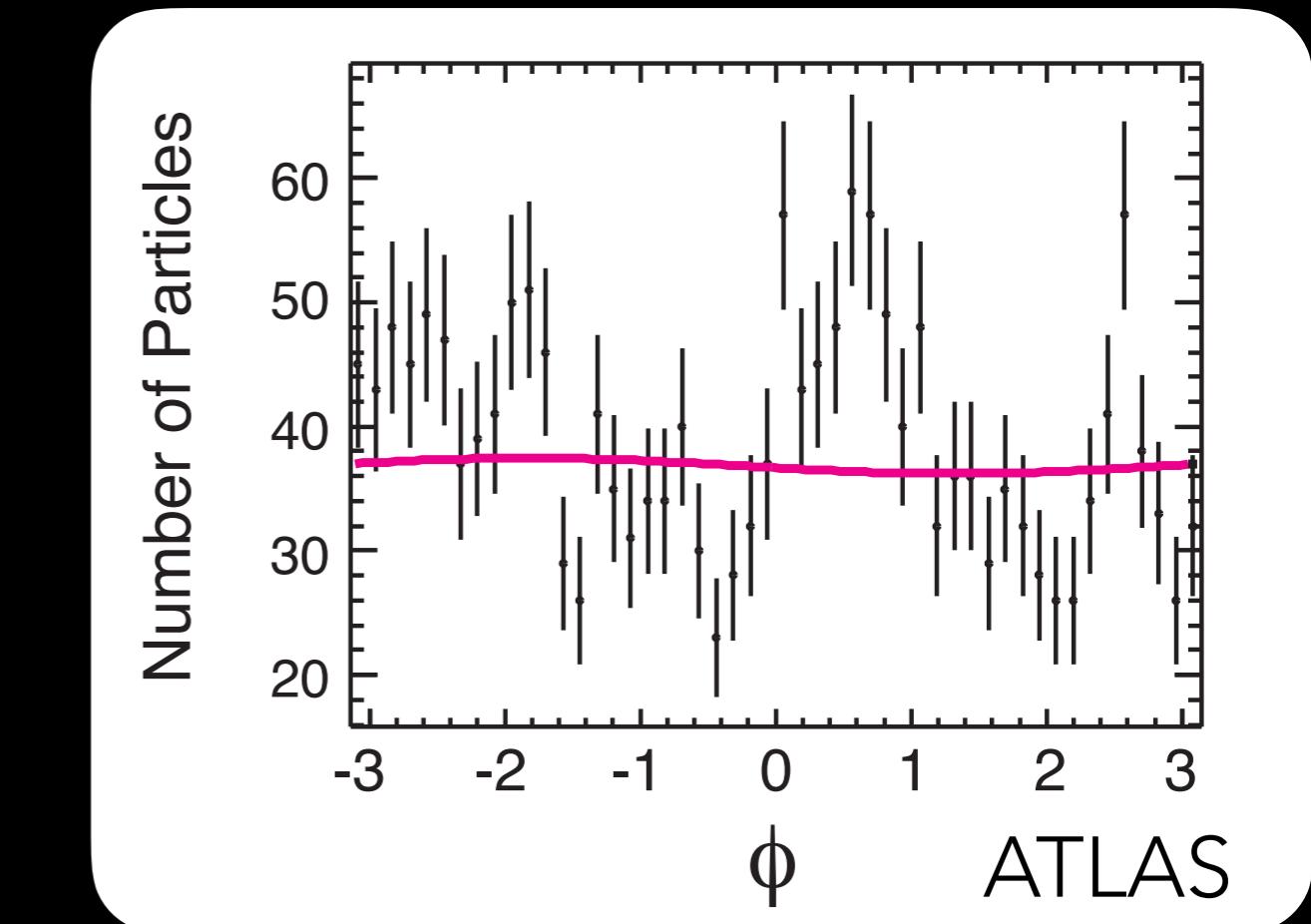
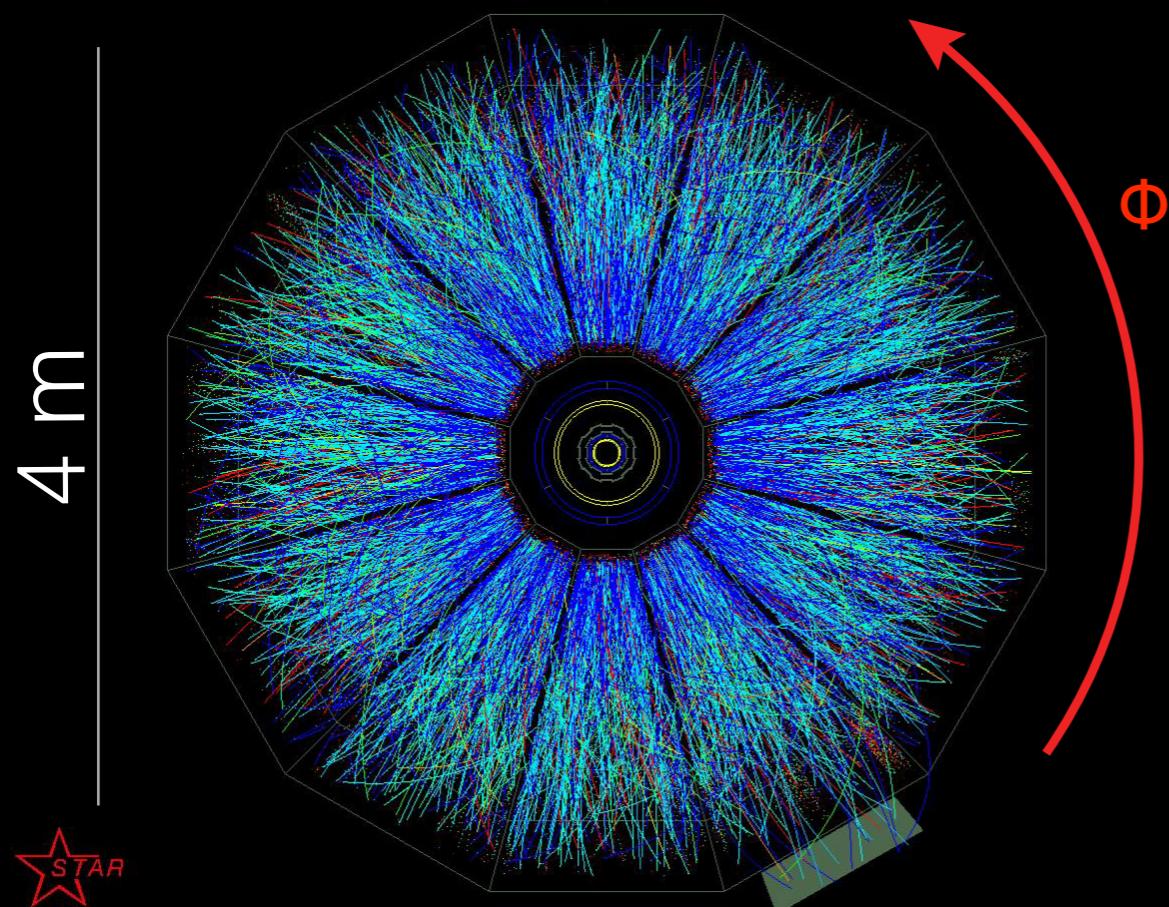


Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left(1 + \sum_n 2v_n \cos[n(\phi - \psi_n)] \right)$$

Azimuthal anisotropies

Anisotropy of particle spectra transverse to the beam line

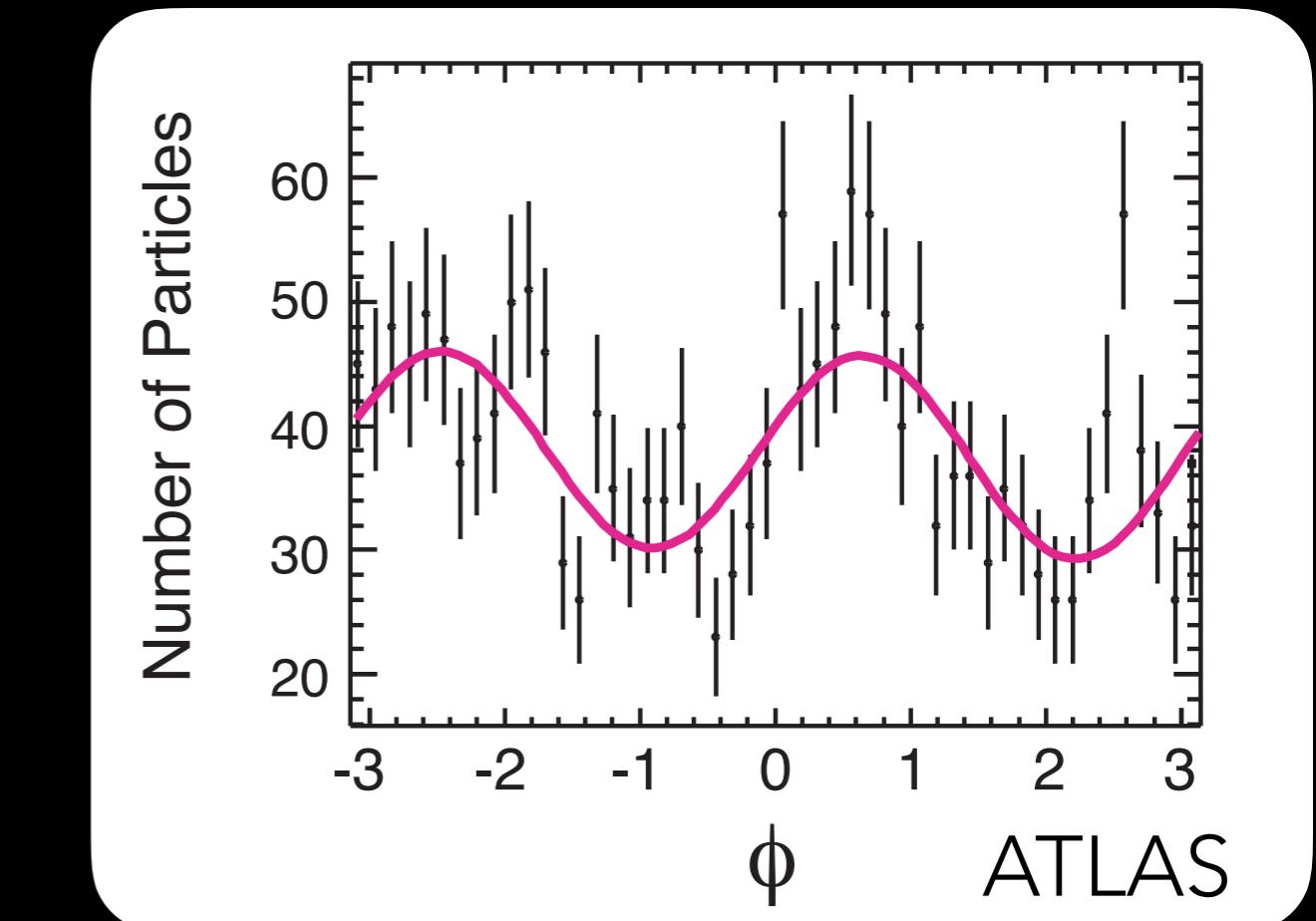
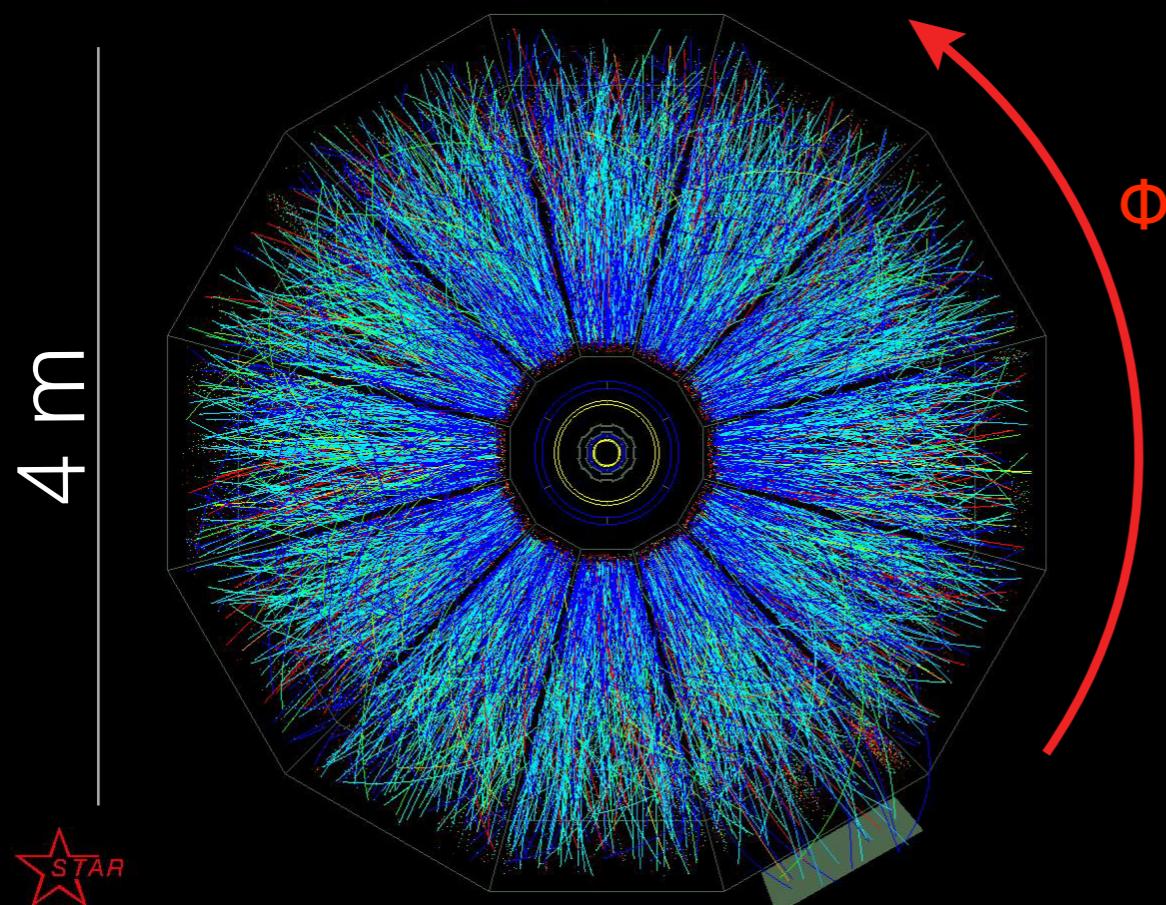


Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi} (1 + v_1 \cos[(\phi - \psi_1)])$$

Azimuthal anisotropies

Anisotropy of particle spectra transverse to the beam line

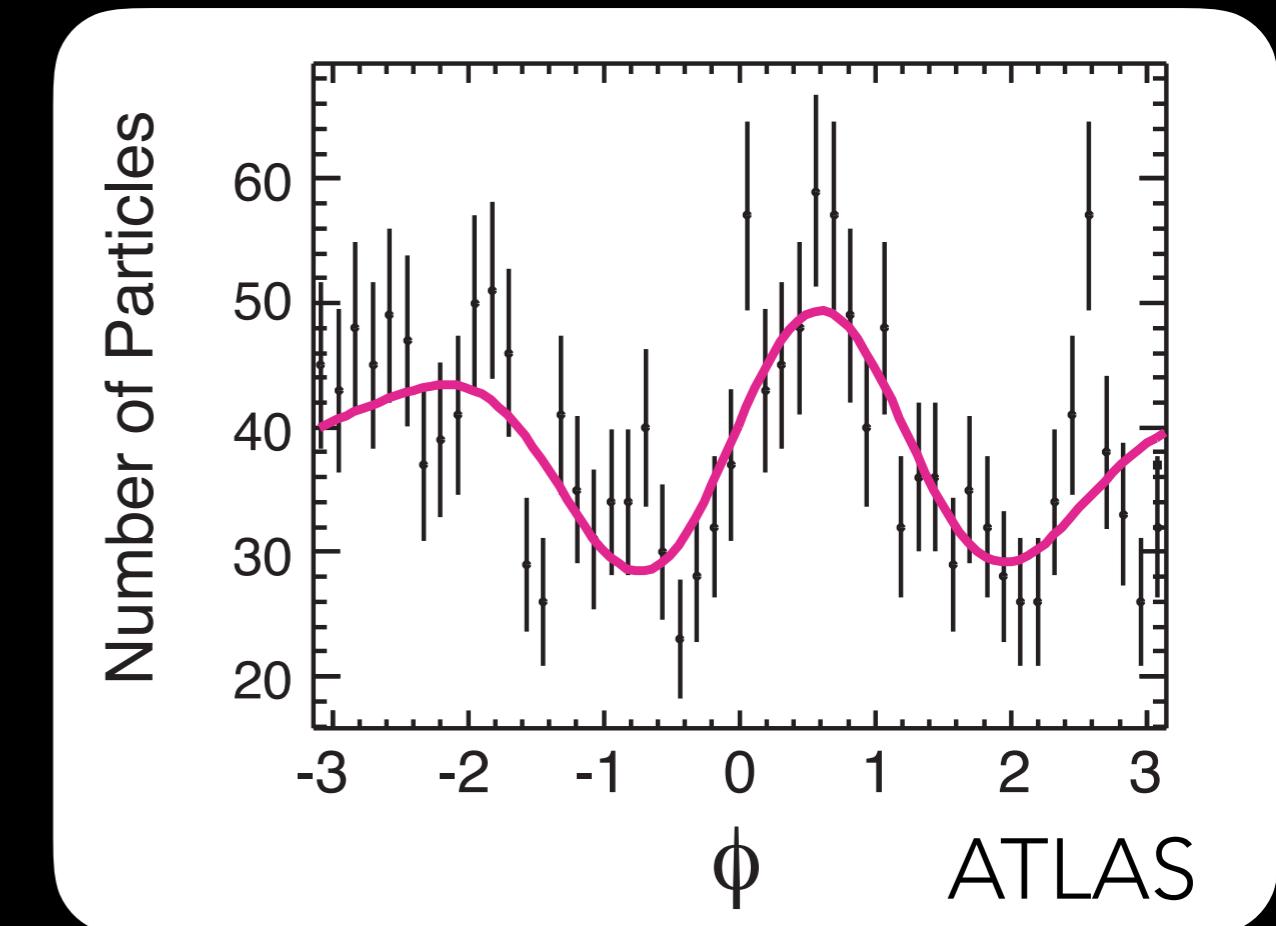
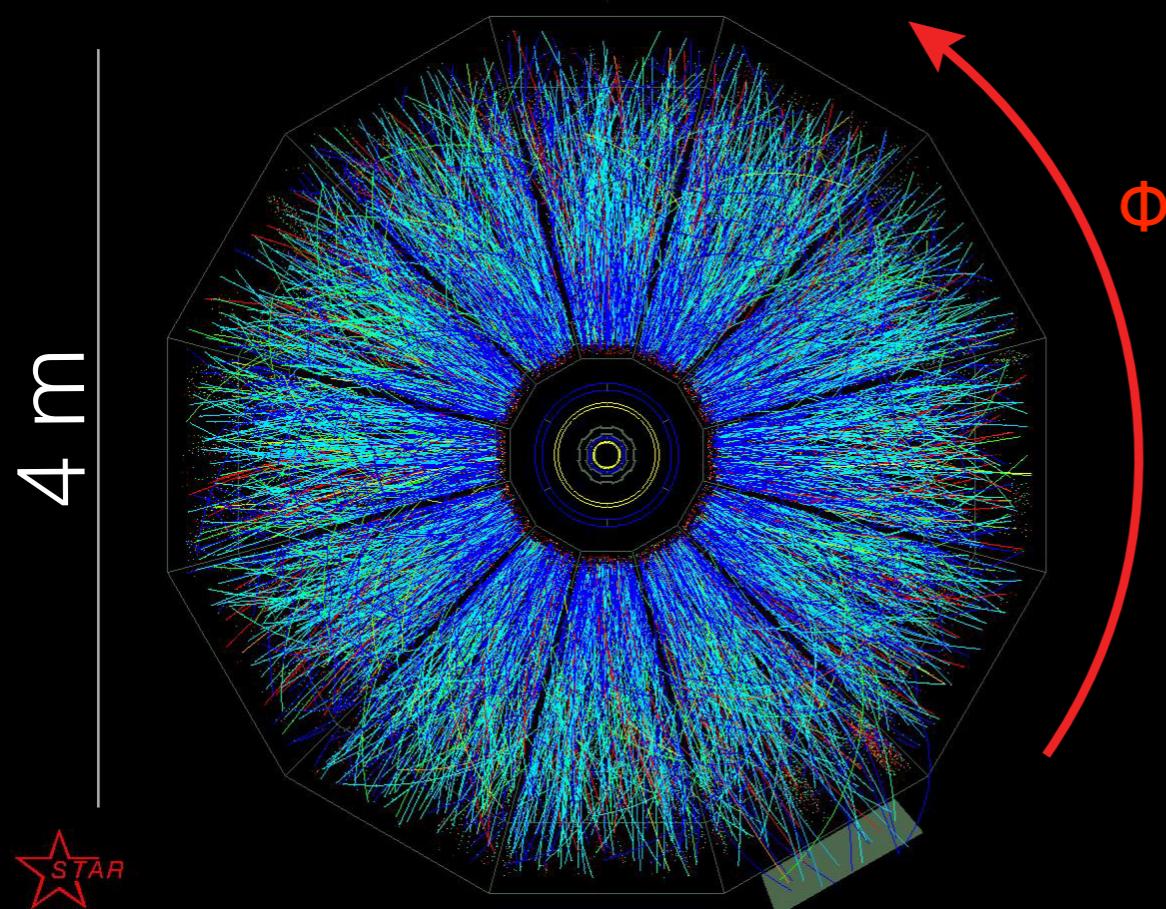


Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi} (1 + v_1 \cos[(\phi - \psi_1)] + v_2 \cos[2(\phi - \psi_2)])$$

Azimuthal anisotropies

Anisotropy of particle spectra transverse to the beam line

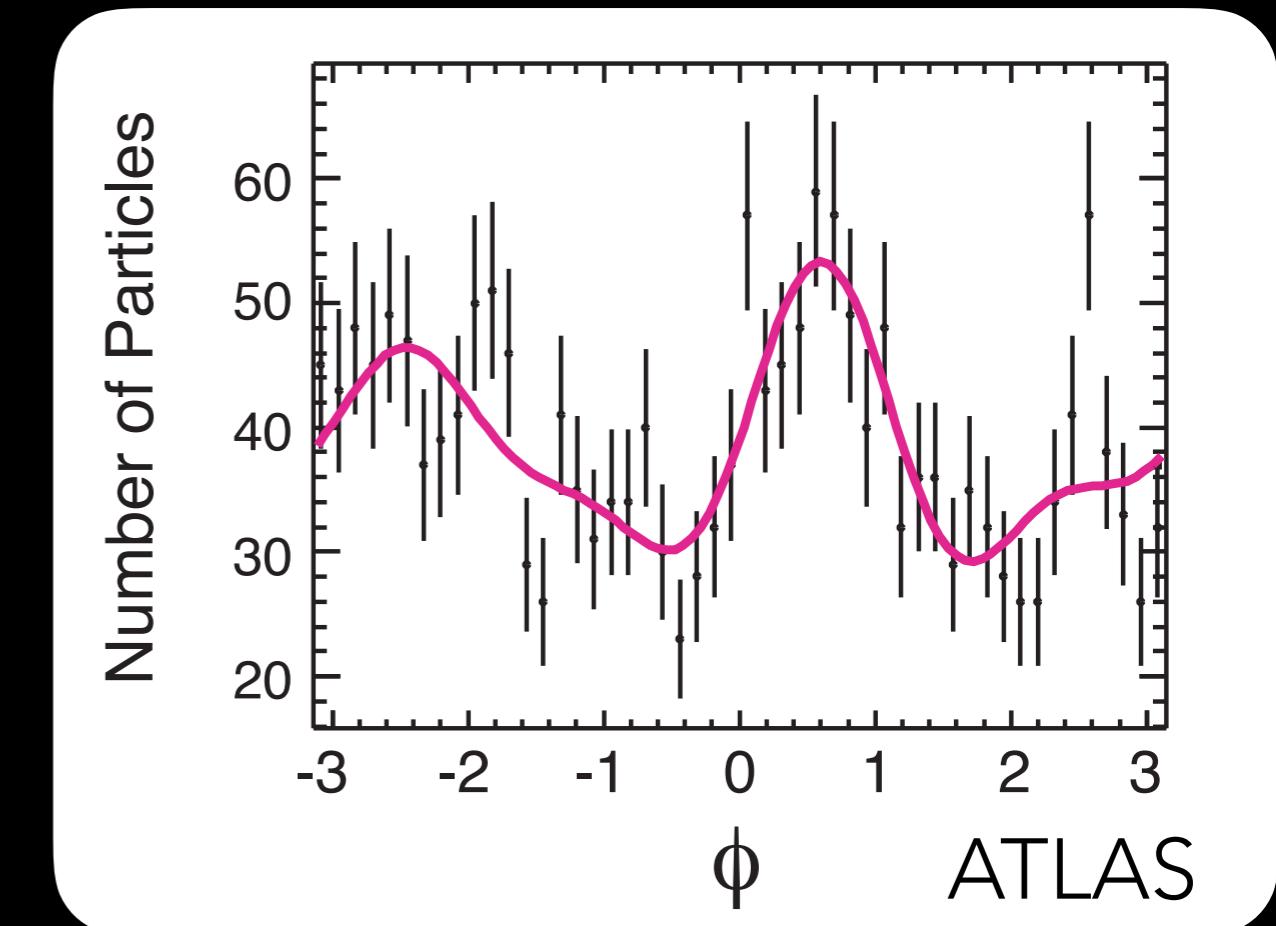
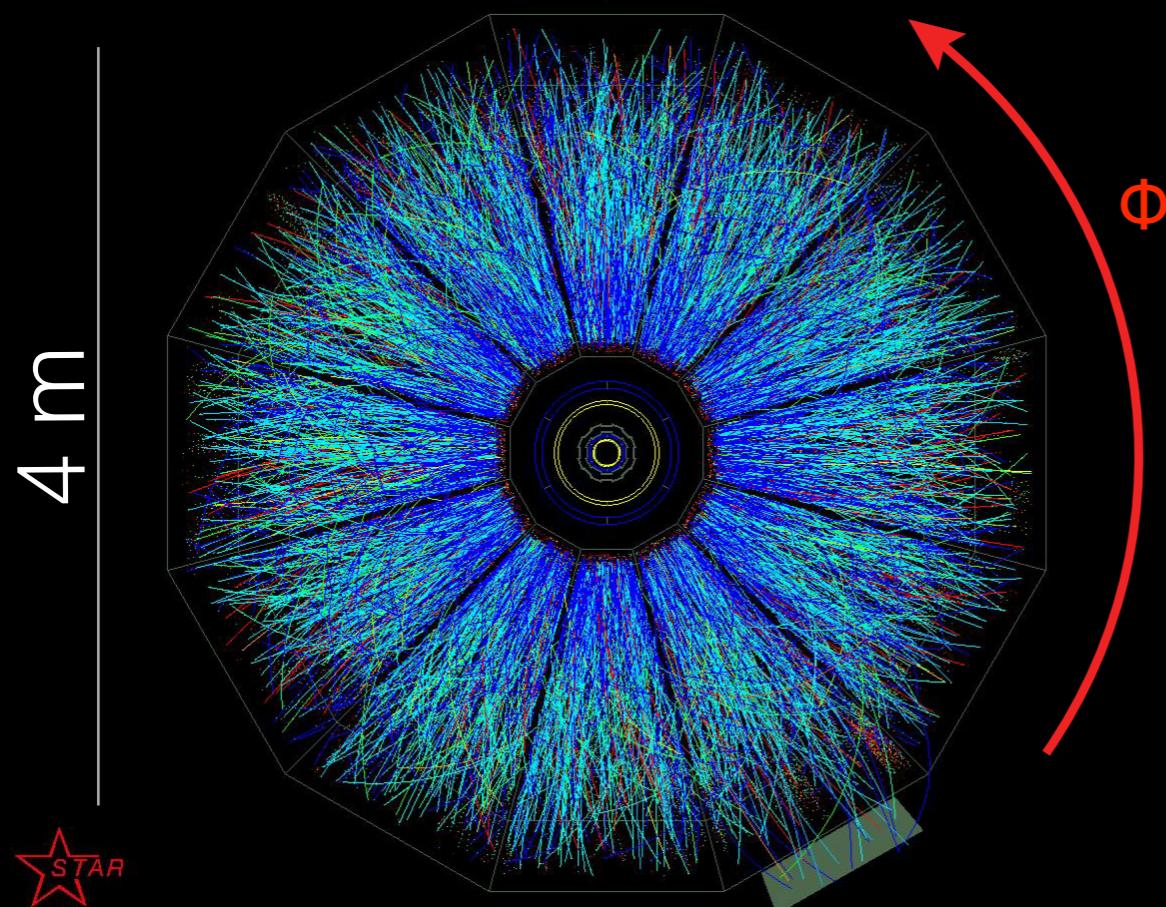


Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi} (1 + v_1 \cos[(\phi - \psi_1)] + v_2 \cos[2(\phi - \psi_2)] + v_3 \cos[3(\phi - \psi_3)])$$

Azimuthal anisotropies

Anisotropy of particle spectra transverse to the beam line

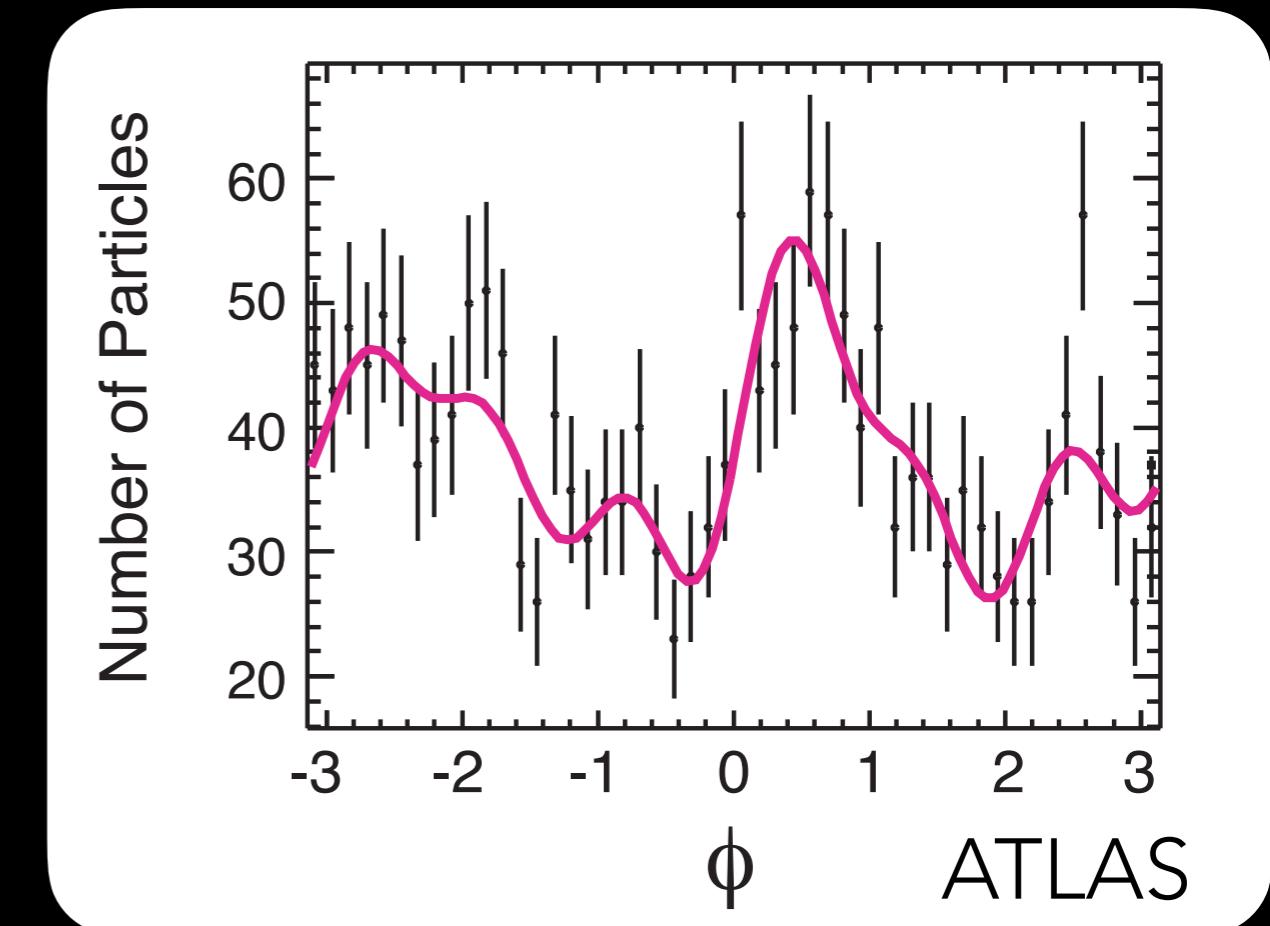
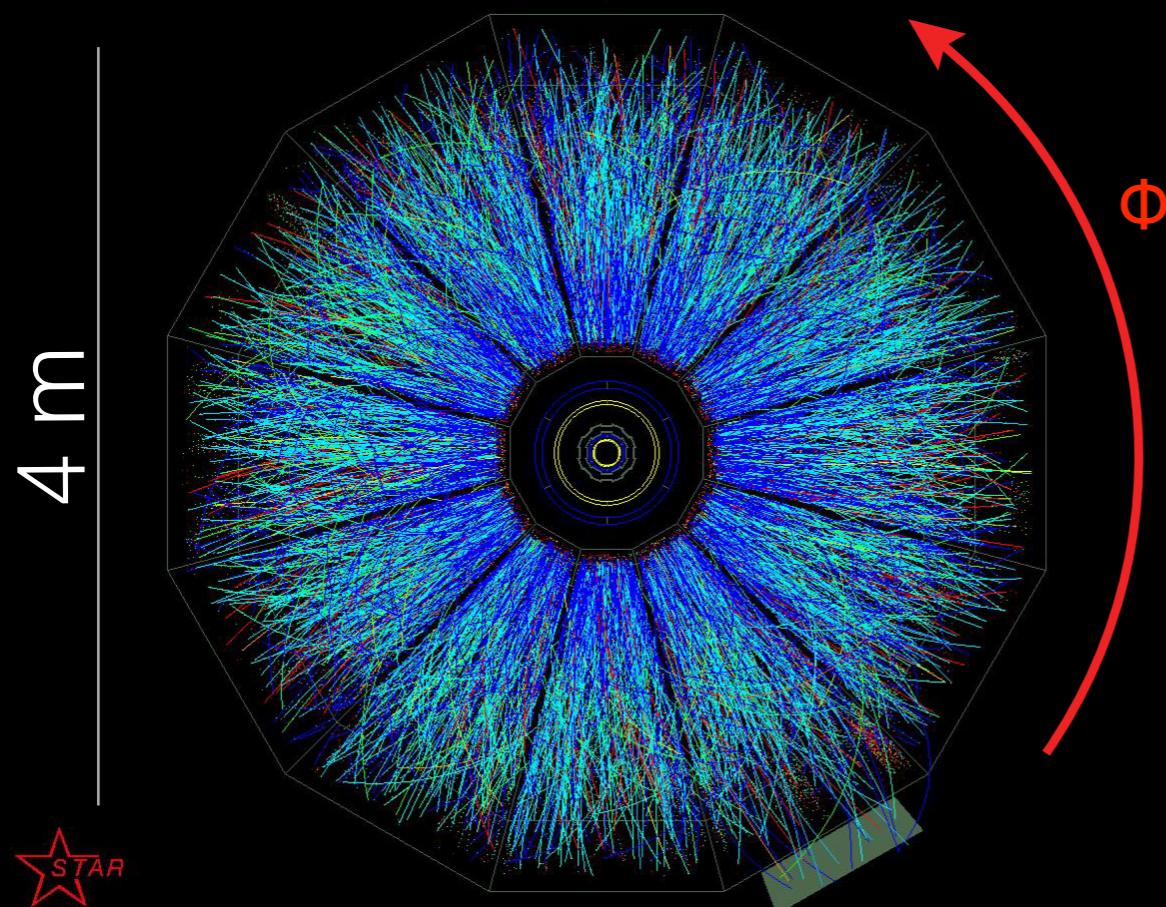


Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi} (1 + v_1 \cos[(\phi - \psi_1)] + v_2 \cos[2(\phi - \psi_2)] + v_3 \cos[3(\phi - \psi_3)] + \dots)$$

Azimuthal anisotropies

Anisotropy of particle spectra transverse to the beam line



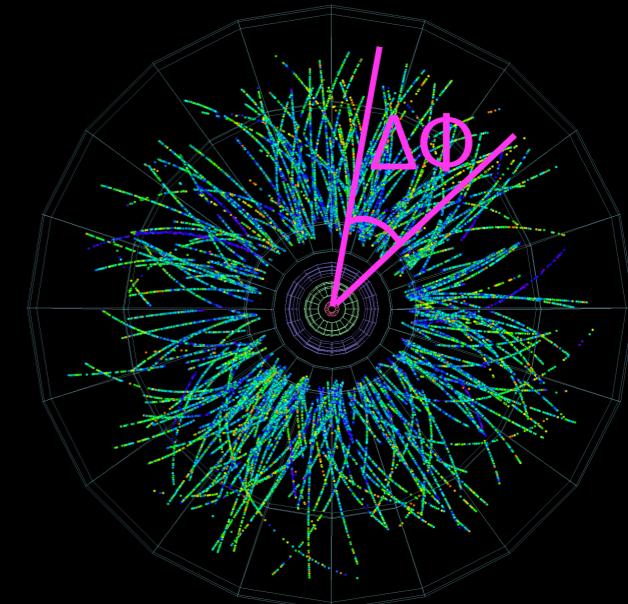
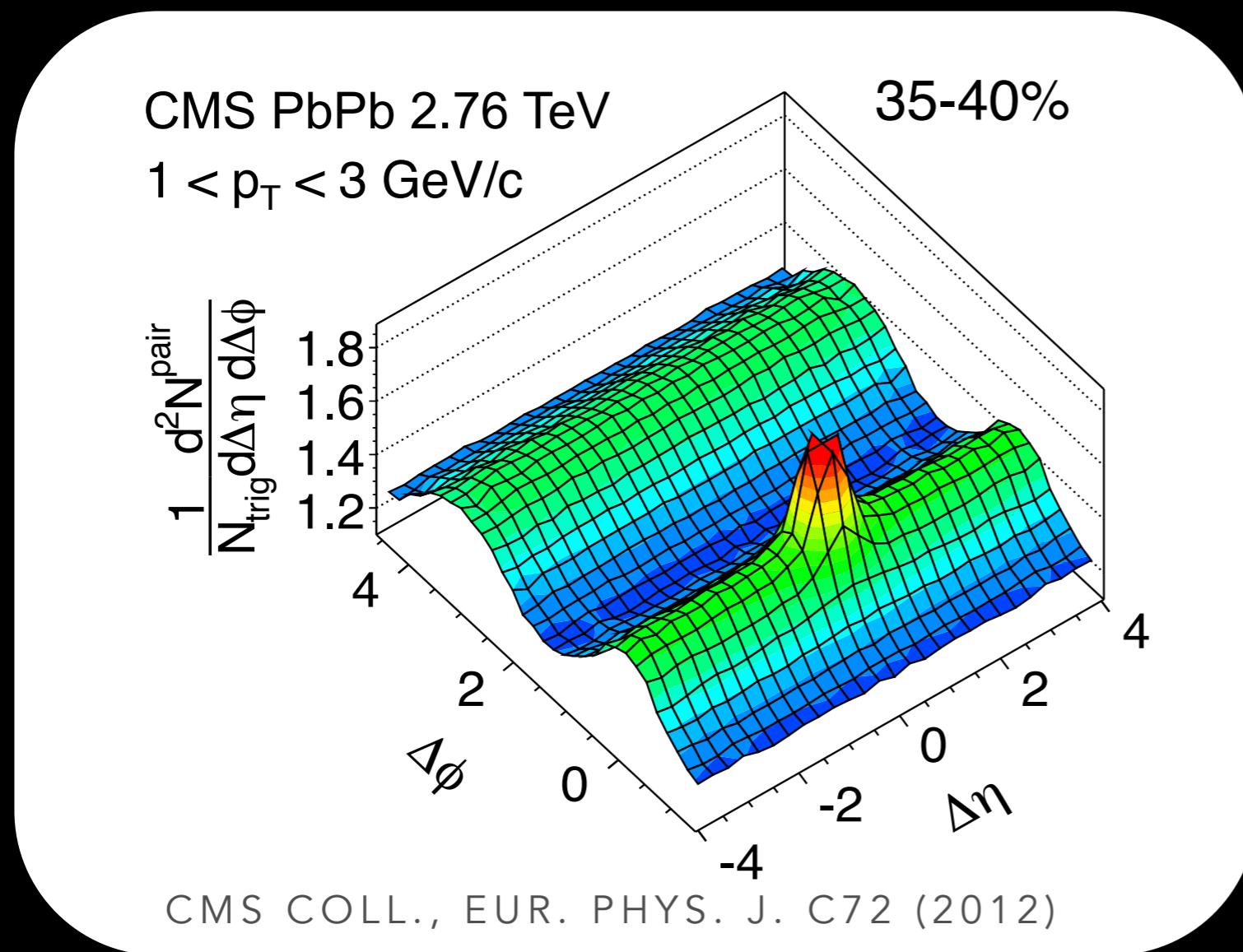
Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi} (1 + v_1 \cos[(\phi - \psi_1)] + v_2 \cos[2(\phi - \psi_2)] + v_3 \cos[3(\phi - \psi_3)] + \dots)$$

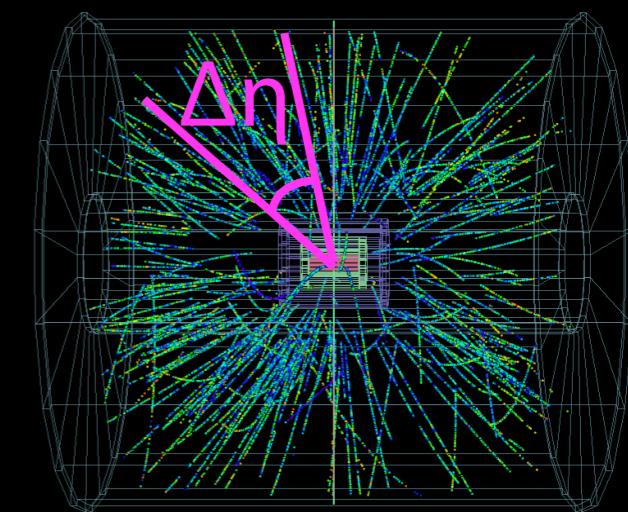
Multi-particle correlations

More efficient and precise to extract v_n using multi-particle correlations

2-particle correlation vs. $\Delta\eta$ and $\Delta\phi$:



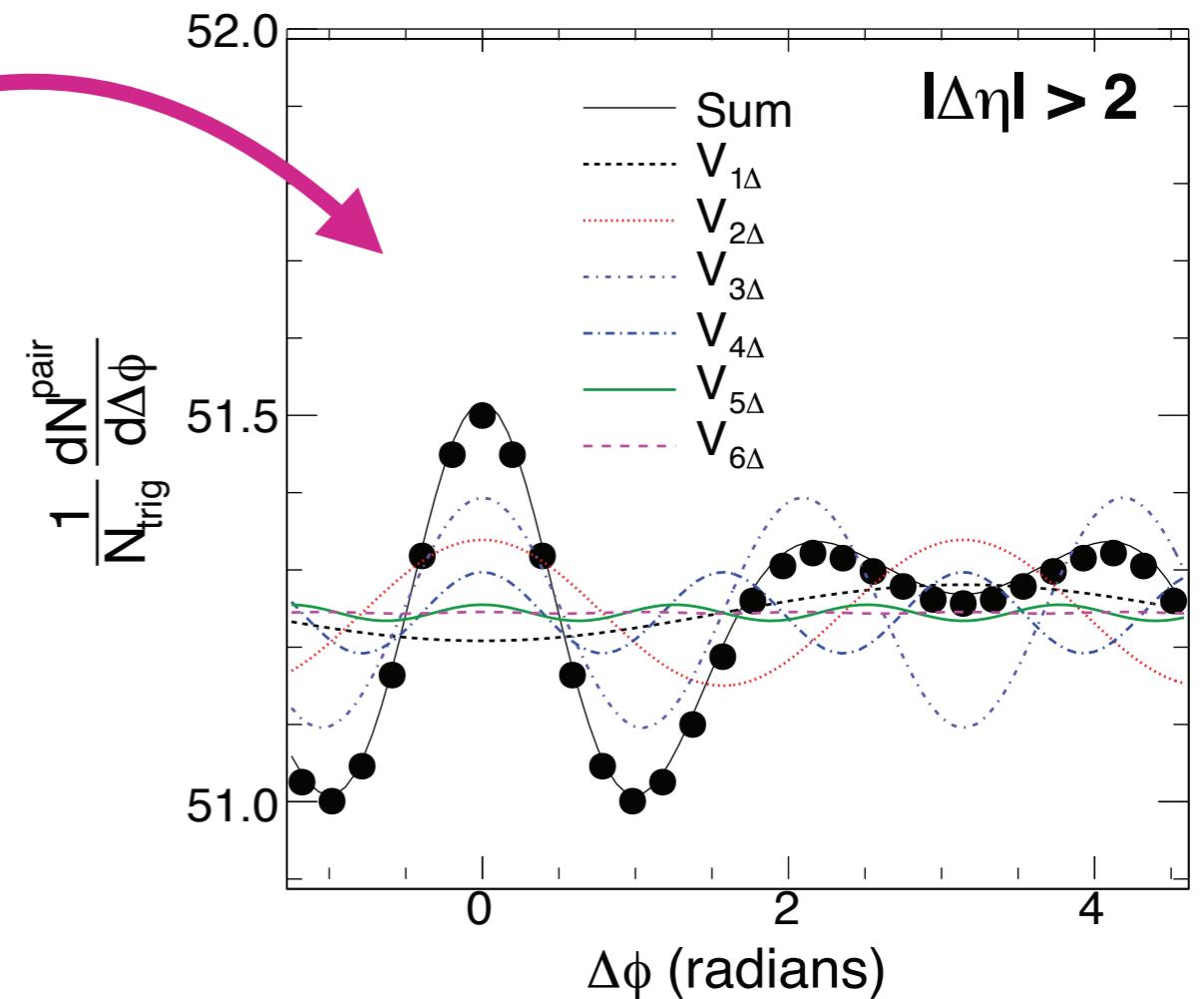
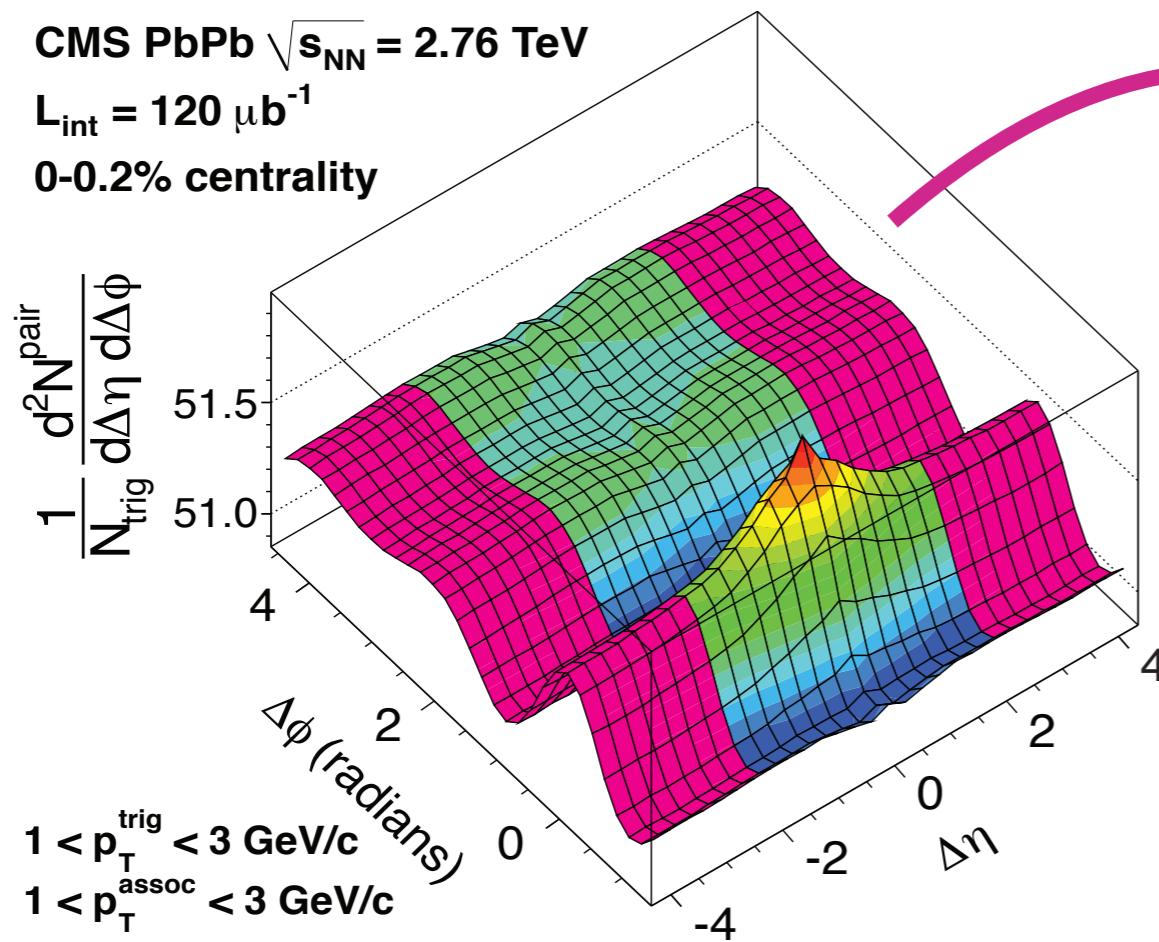
$\Delta\phi$: DIFFERENCE
IN AZIMUTHAL ANGLE



$\Delta\eta$: DIFFERENCE
IN PSEUDO-RAPIDITY

Ridge structure and anisotropic flow

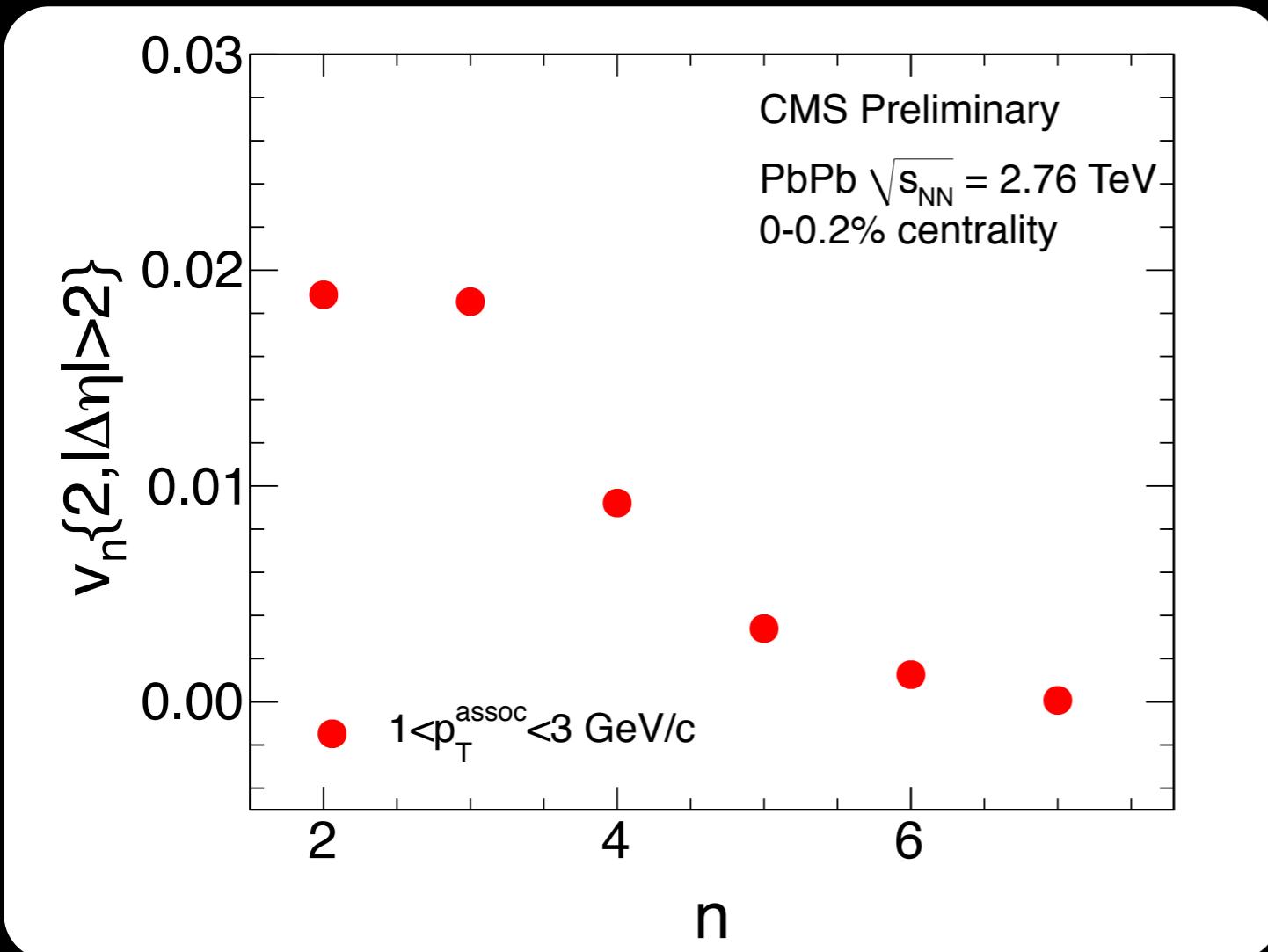
Fourier expansion of the 2-particle distribution



$$\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} \sim 1 + 2 \sum_{n=1}^{n=\infty} V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}}) \cos(n\Delta\phi) \quad v_n = \sqrt{V_{n\Delta}}$$

Ridge structure and anisotropic flow

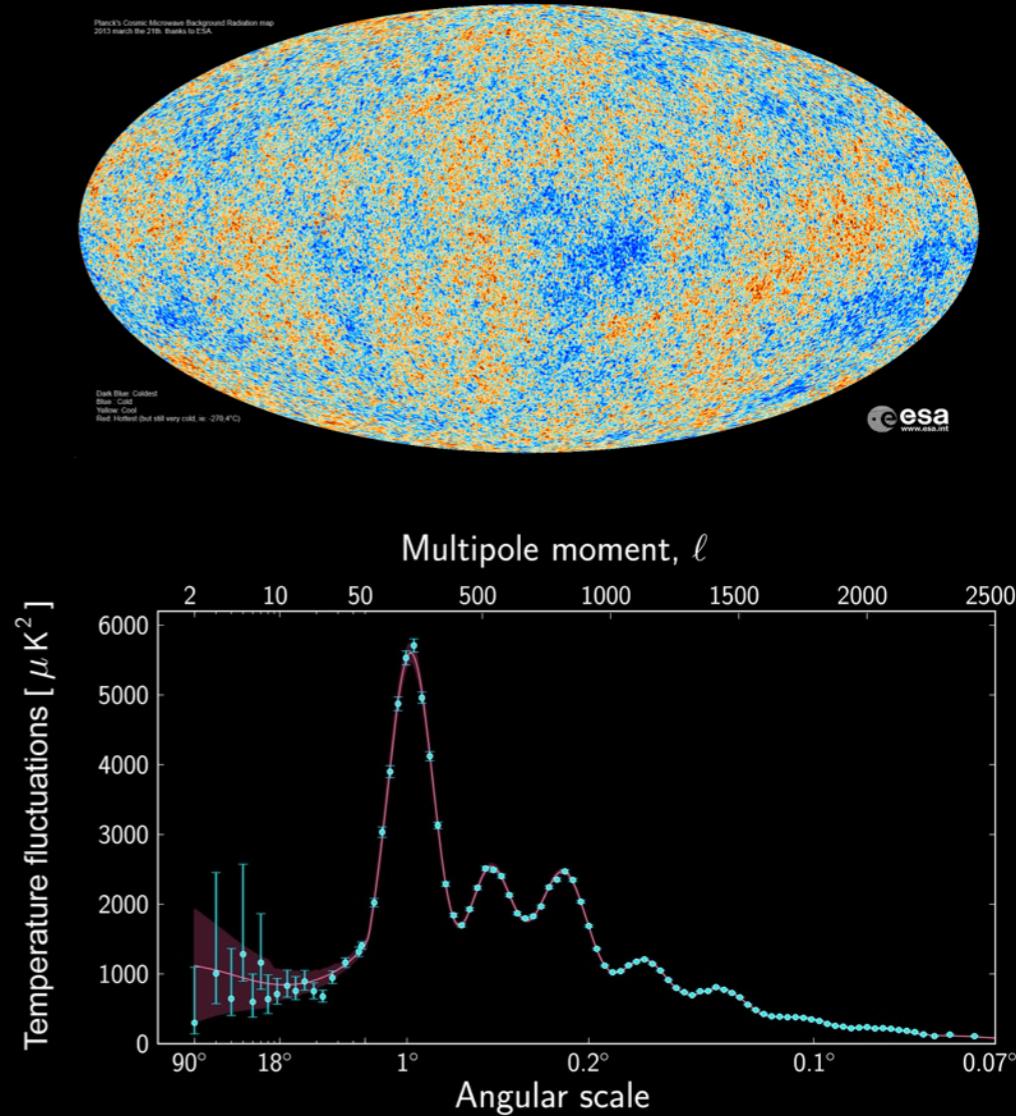
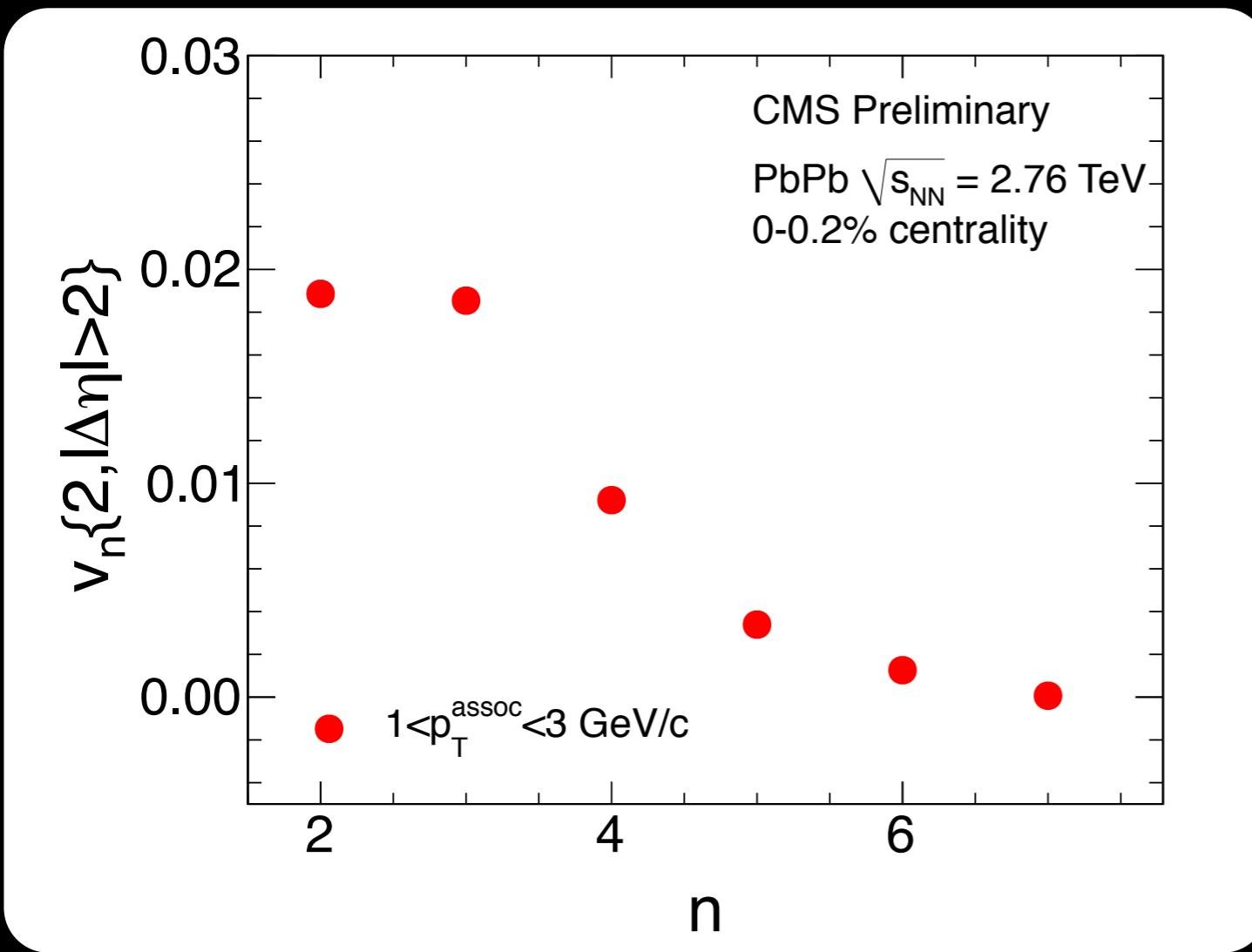
v_n as a function of n in central Pb+Pb collisions



$$\frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta\phi} \sim 1 + 2 \sum_{n=1}^{n=\infty} V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}}) \cos(n\Delta\phi) \quad v_n = \sqrt{V_{n\Delta}}$$

Ridge structure and anisotropic flow

v_n as a function of n in central Pb+Pb collisions



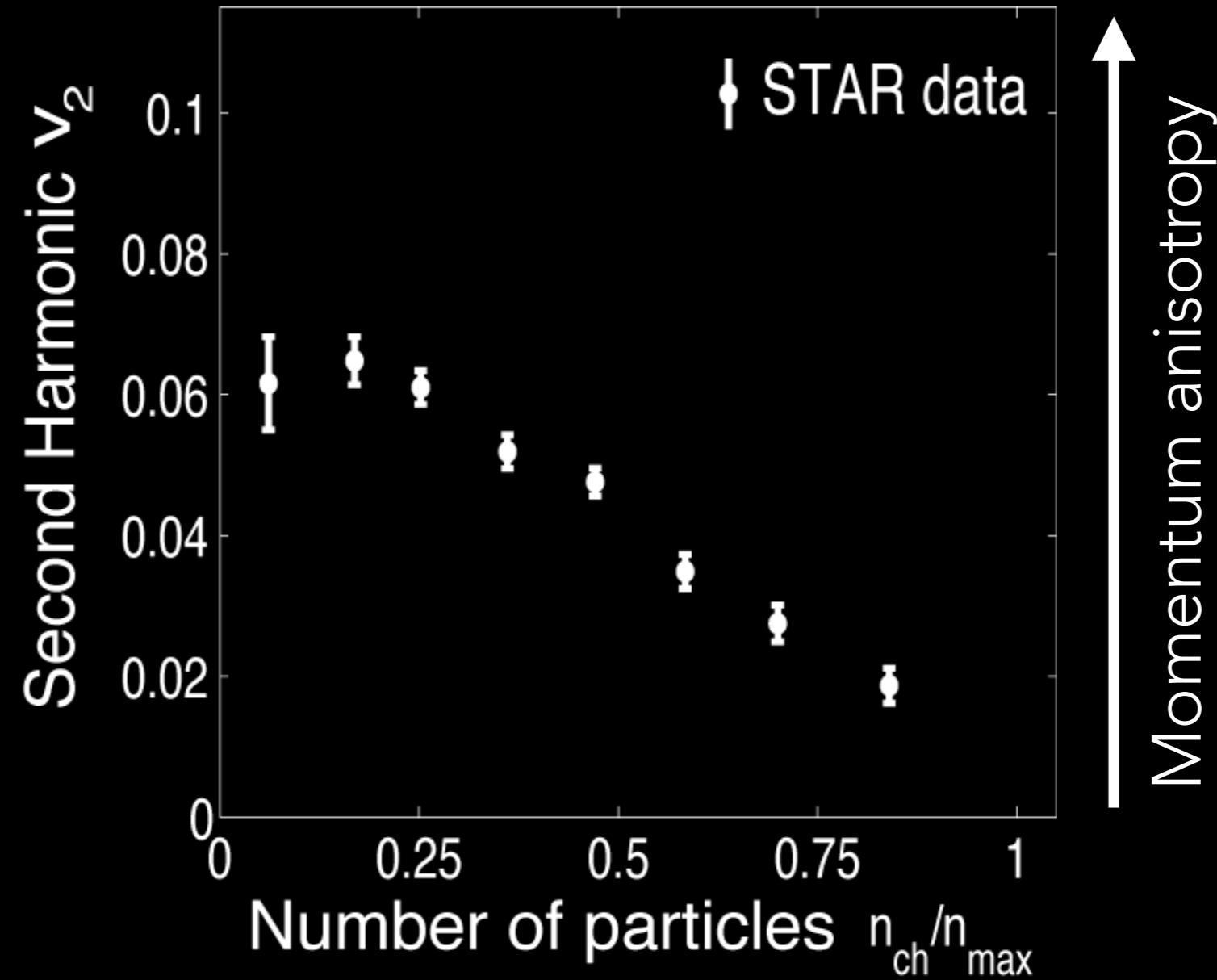
$$\frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta\phi} \sim 1 + 2 \sum_{n=1}^{n=\infty} V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}}) \cos(n\Delta\phi)$$

$$v_n \sim \sqrt{V_{n\Delta}}$$

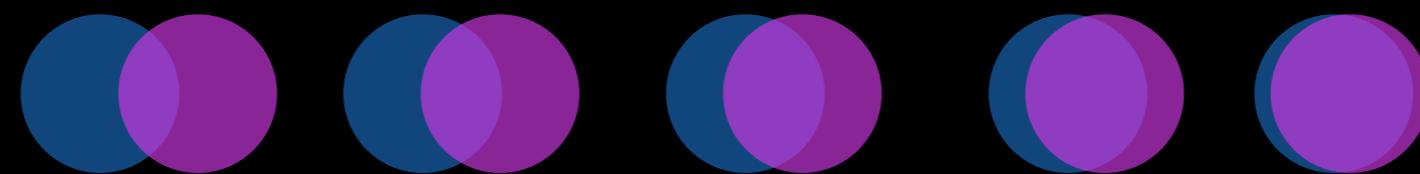
Centrality dependence

Correlation between initial shape and momentum anisotropy

STAR Collaboration, Phys.Rev.Lett. 86 (2001) 402-407

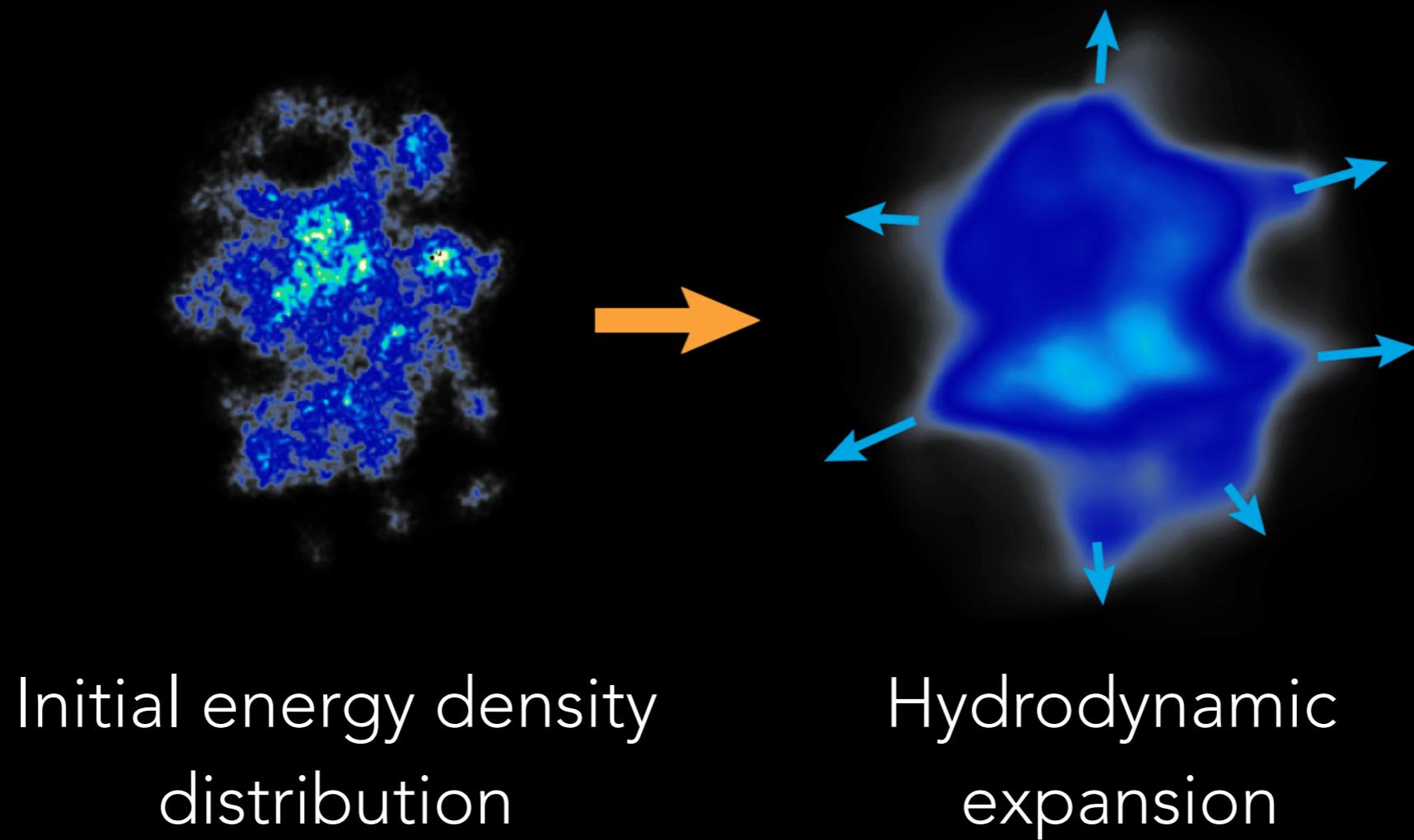


Initial shape:



Interpretation: Strong final state effects

- Long range $\Delta\eta$ correlations emerge from early times (causality)
- Azimuthal structure formed by the medium response to the fluctuating initial transverse geometry



Need for effective theories of QCD

Complex many-body systems are not well described by simple extrapolation from properties of a few particles

Need effective theories to describe emergent phenomena: *Phase transitions, critical phenomena, hydrodynamic behavior, gluon saturation, plasma instabilities, ...*

4 August 1972, Volume 177, Number 4047

SCIENCE

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it

- **Color Glass Condensate** - valid at high energy, includes gluon saturation at high densities (at small x and small transverse momentum $p_T \lesssim Q_S$)
→ Compute the initial conditions for nuclear collisions

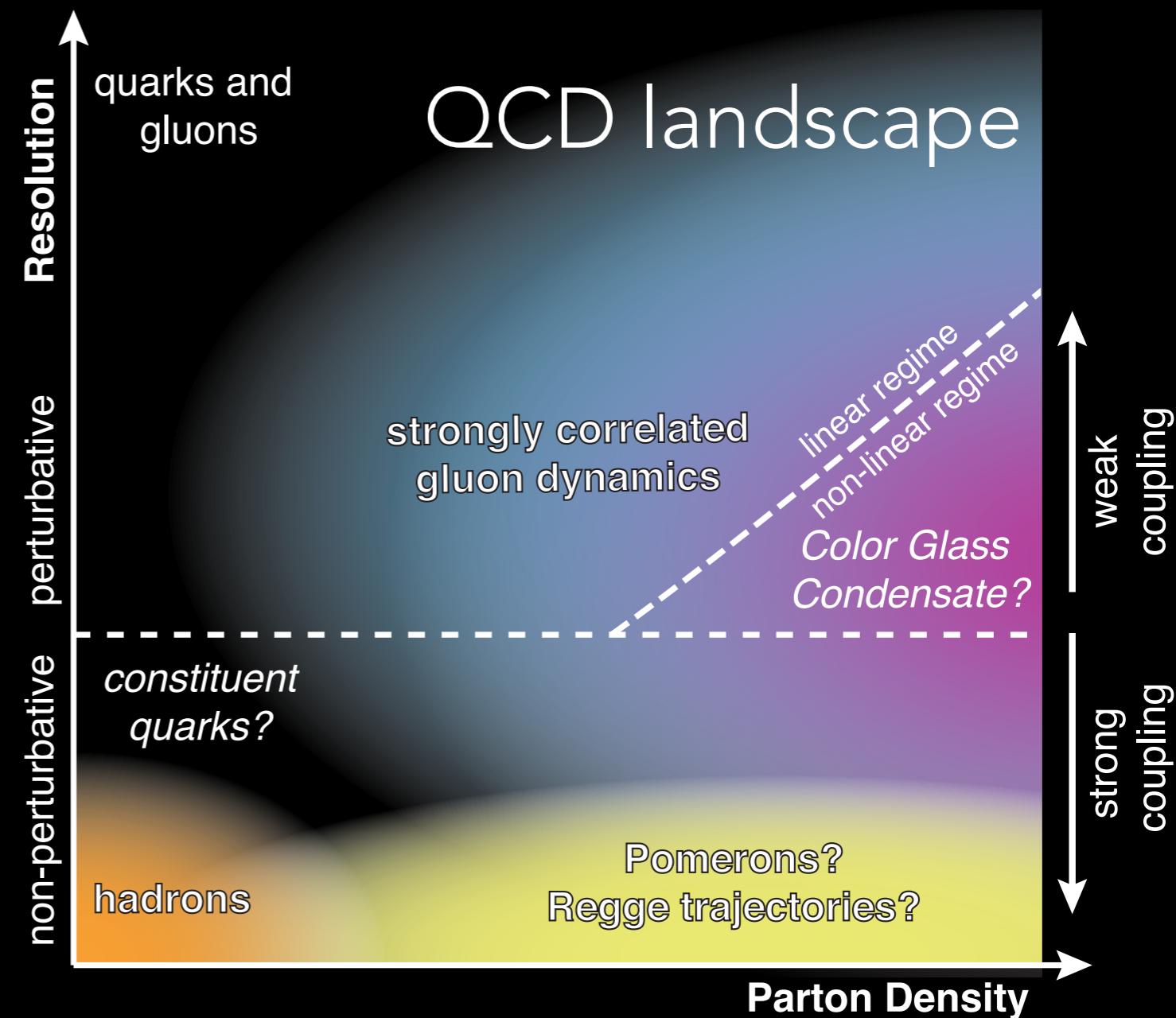
B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

- **Relativistic hydrodynamics**
→ Compute the final state dynamical evolution

Initial state from an effective theory of QCD

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Limit of high energy and high parton density
- Weak coupling but strongly interacting
- Non-linear effects:
Gluon saturation
at $p_T \lesssim Q_s(x, b)$
- Occupation # $\sim 1/\alpha_s$
Classical description:
Solve Yang-Mills equations!
- Leading quantum corrections can be included via small-x evolution

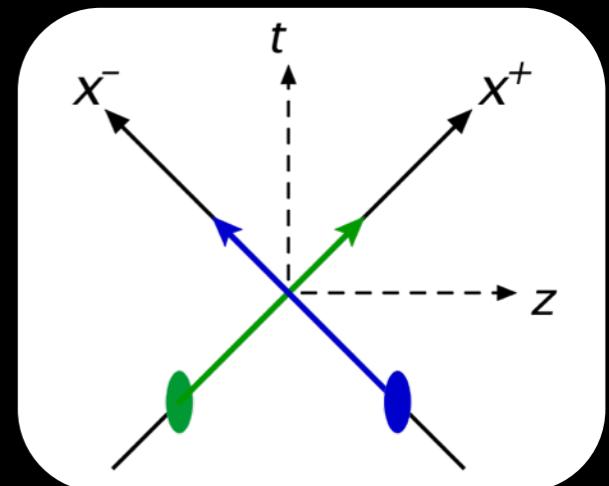
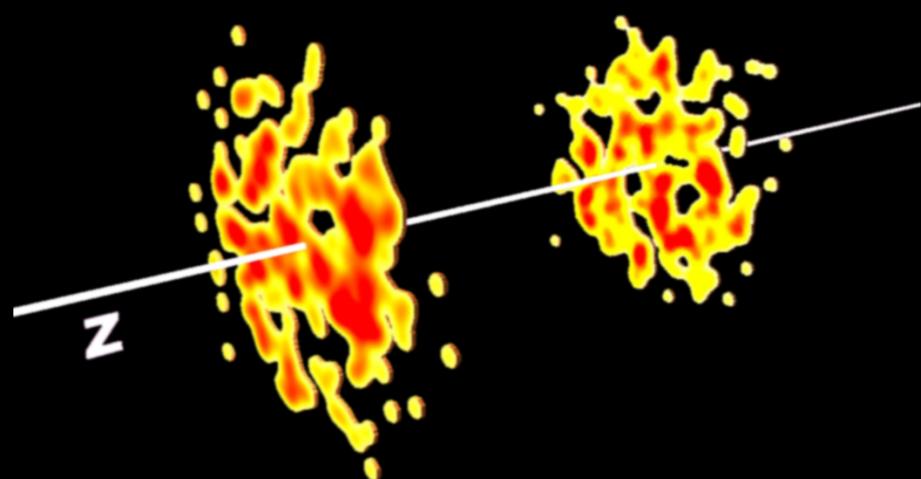


IP-Glasma initial state

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

Particle production governed by the **Yang Mills equations**

$$[D_\mu, F^{\mu\nu}] = J^\nu$$



Incoming currents

How to determine the incoming currents J^ν :

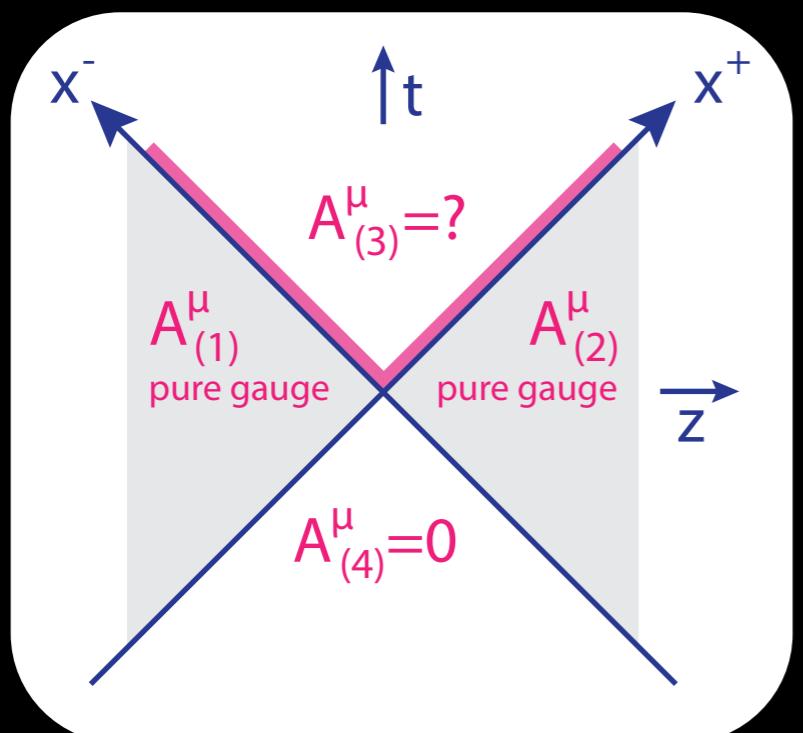
- IP-Sat model: Parametrize energy and spatial dependence of deep inelastic cross section - fit parameters to HERA data
[Kowalski, Teaney, Phys.Rev. D68 \(2003\) 114005](#)
- → energy and position dependent saturation scale $Q_s(x, \mathbf{x}_T)$
- Sample nucleons and color charges with density $\sim Q_s(x, \mathbf{x}_T)$

IP-Glasma initial state

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

Particle production governed by the **Yang Mills equations**

$$[D_\mu, F^{\mu\nu}] = J^\nu$$



Gauge fields in
Schwinger gauge

$$A_{(3)}^i|_{\tau=0^+} = A_{(1)}^i + A_{(2)}^i$$
$$A_{(3)}^\eta|_{\tau=0^+} = \frac{ig}{2}[A_{(1)}^i, A_{(2)}^i]$$

We solve for the gluon
fields numerically

Kovner, McLerran, Weigert, Phys. Rev. D52, 6231 (1995)
Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237

From gluon fields to hydrodynamics

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Compute energy-momentum tensor $T^{\mu\nu}$ of the gluon fields
- Extract energy density and flow vector via $u_\mu T^{\mu\nu} = \varepsilon u^\nu$ for every transverse position
- This provides boost invariant initial conditions for fluid dynamic simulations
- At the moment set initial $\Pi^{\mu\nu} = 0$
We improve on this when studying small systems

Relativistic fluid dynamics

- Effective theory for the long wavelength modes, valid for a strongly interacting system
- Basic equations: **energy and momentum conservation**

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \Pi^{\mu\nu}$$

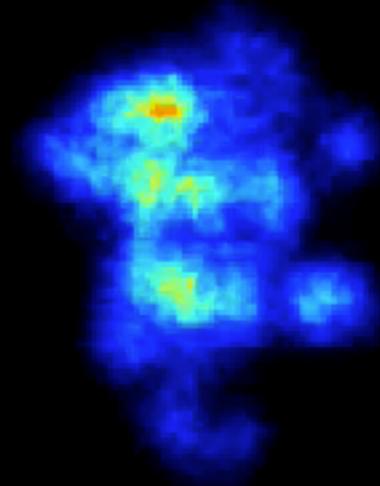
↓ ↓
energy density pressure
↑
flow velocity viscous correction

- + constituent equations for $\Pi^{\mu\nu}$
(contains shear viscosity η and bulk viscosity ζ , possibly heat conductivity and higher order transport coefficients)
- Equation of state $P(\varepsilon)$ relates pressure to energy density (lattice)

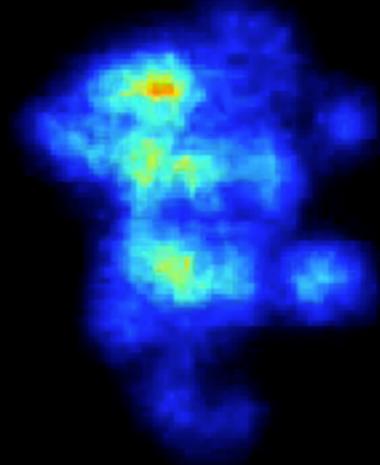
Effect of shear viscosity

C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 110, 012302 (2013)

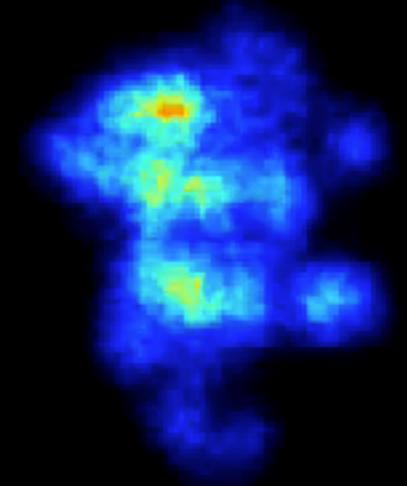
$$\eta/s = 0$$



$$\eta/s = 0.1$$



$$\eta/s = 0.2$$



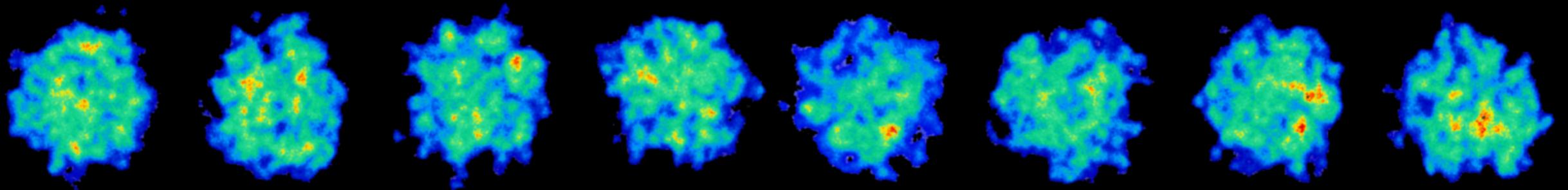
$t = 0.40 \text{ fm}$

MUSIC hydrodynamic simulation

B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys. Rev. Lett. 106, 04230 (2011)

Event-by-event hydrodynamic simulations

C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 110, 012302 (2013)

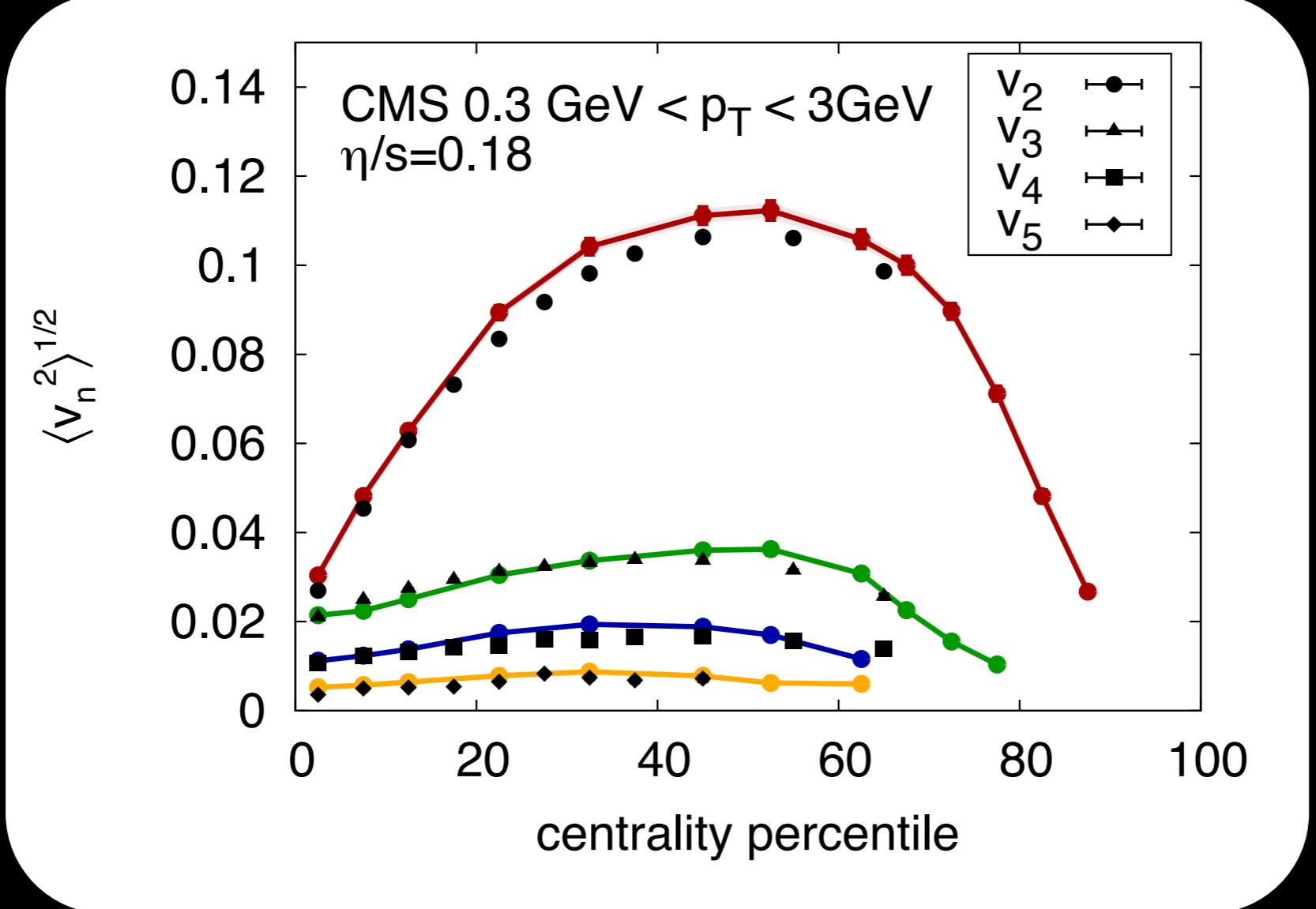


- Evolve many initial shapes using viscous fluid dynamics
- Convert energy density to particles ("freeze-out")
- Compute particle correlations
- Compare to experimental data

Flow harmonics v_n from IP-Glasma initial state and MUSIC hydrodynamics

C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 110, 012302 (2013)

B. Schenke, R. Venugopalan, Phys.Rev.Lett. 113 (2014) 102301



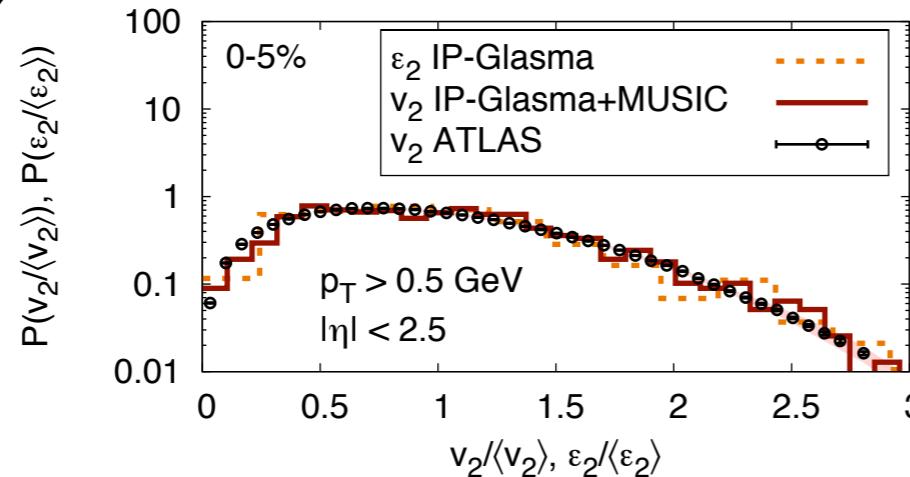
Event-by-event distributions of flow harmonics

ATLAS Collaboration, JHEP 1311 (2013) 183

C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, PRL110, 012302 (2013)

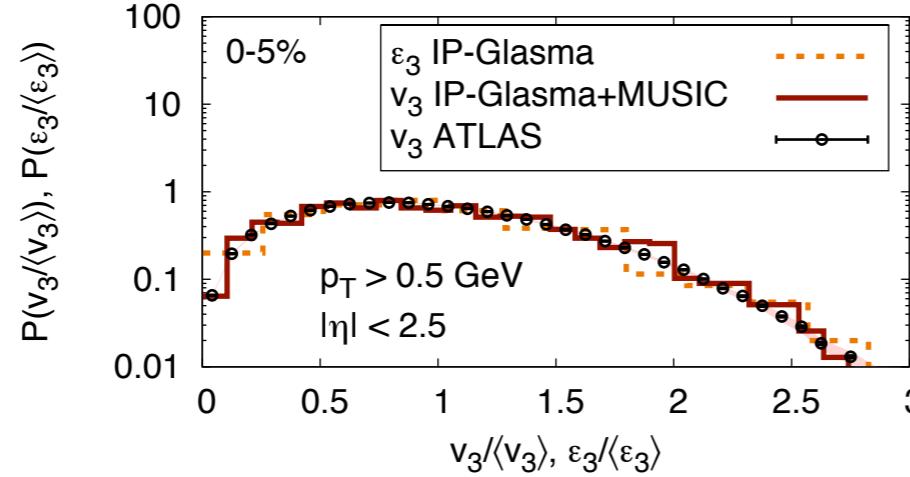
v_2

0-5%

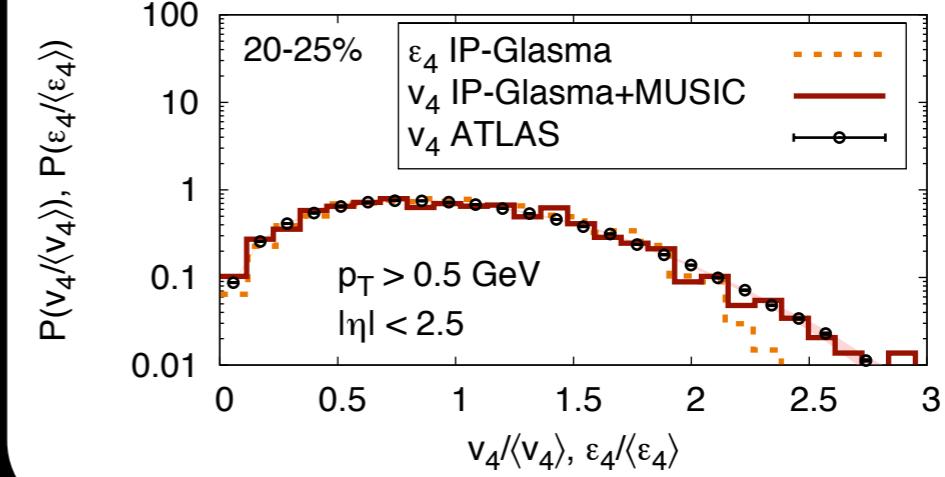
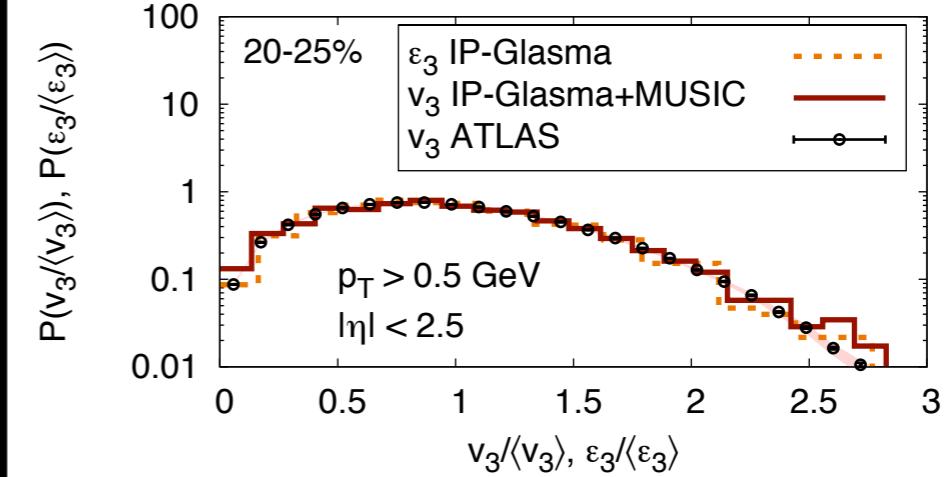
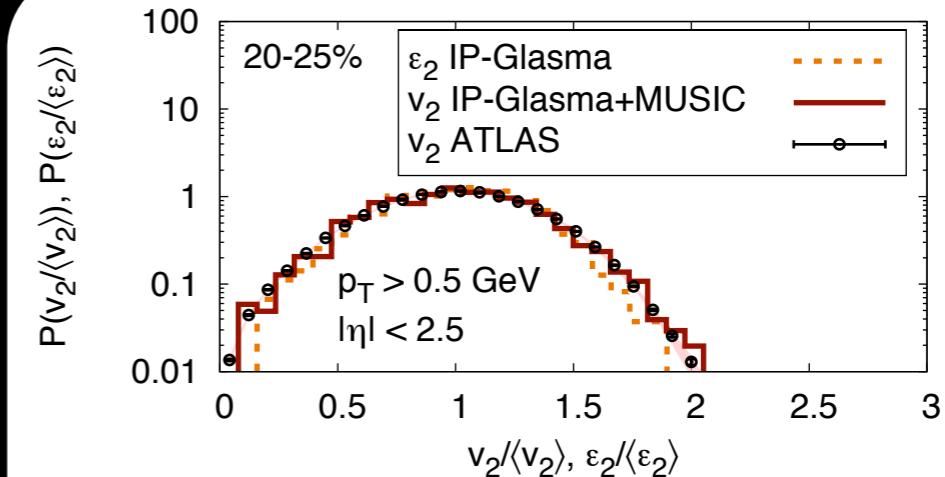
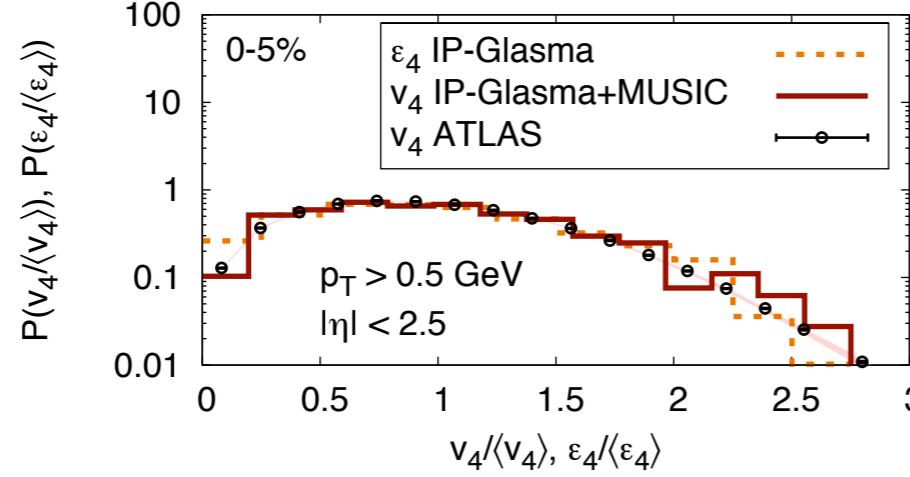


v_3

20-25%



v_4



Event-by-event v_n helped exclude models

Scaled event-by-event v_n are independent of transport properties:
Discriminate between different initial state models

Only three models left:

IP-Glasma (that I introduced)

[C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, PRL110, 012302 \(2013\)](#)

EKRT (that uses pQCD and a saturation model)

[H. Niemi, K.J. Eskola, R. Paatelainen, Phys.Rev. C93 \(2016\) no.2, 024907](#)

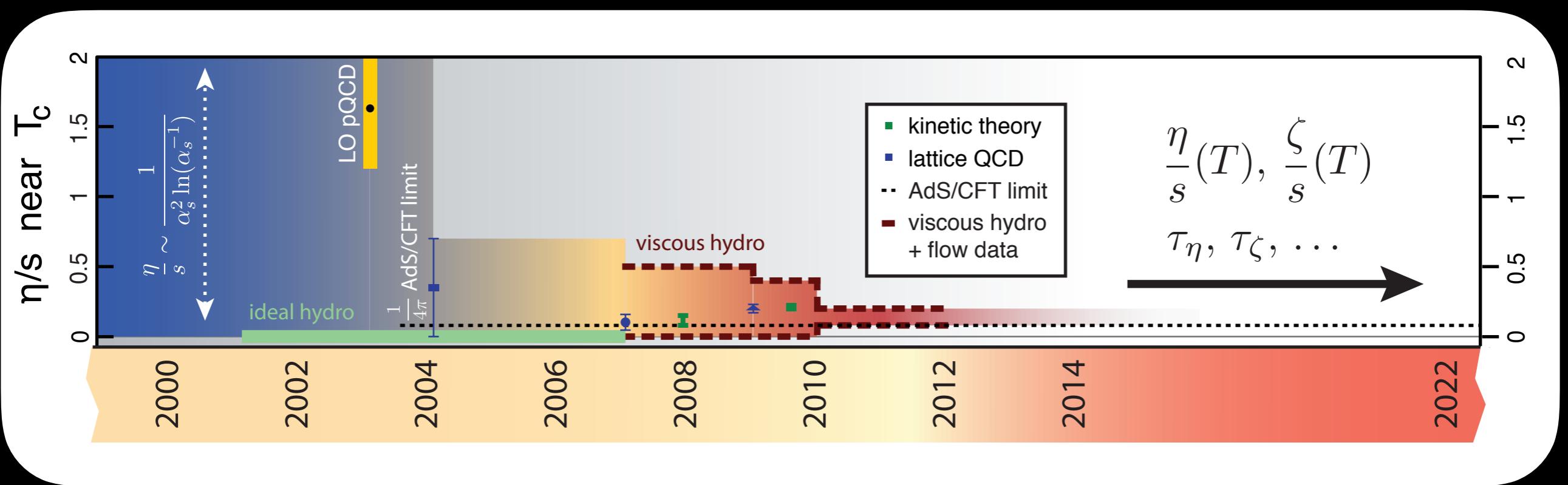
Trento (parametrized energy deposition as in the IP-Glasma)

[J.S. Moreland, J. E. Bernhard, S.A. Bass, Phys.Rev. C92 \(2015\), 011901](#)

[J.E. Bernhard, J.S. Moreland, S.A. Bass, J. Liu, U. Heinz, Phys.Rev. C94 \(2016\), 024907](#)

Improved understanding of QCD shear viscosity

Event-by-event viscous hydrodynamic simulations with
QCD based initial states can help extract transport properties



LO pQCD:

P. Arnold, G. D. Moore, L. G. Yaffe, JHEP 0305 (2003) 051

AdS/CFT:

P. Kovtun, D. T. Son, A. O. Starinets, Phys.Rev.Lett. 94 (2005) 111601

Lattice QCD:

A. Nakamura, S. Sakai, Phys.Rev.Lett. 94 (2005) 072305

H. B. Meyer, Phys.Rev. D76 (2007) 101701; Nucl.Phys. A830 (2009) 641C-648C

Ideal hydro:

P. F. Kolb, J. Sollfrank, U. W. Heinz, Phys.Rev. C62 (2000) 054909

P. F. Kolb, P. Huovinen, U. W. Heinz, H. Heiselberg, Phys.Lett. B500 (2001) 232-240

pQCD/kin. theory: Z. Xu, C. Greiner, H. Stöcker, Phys.Rev.Lett. 101 (2008) 082302

J.-W. Chen, H. Dong, K. Ohnishi, Q. Wang, Phys.Lett. B685 (2010) 277-282

Viscous hydro:

P. Romatschke, U. Romatschke, Phys.Rev.Lett. 99 (2007) 172301

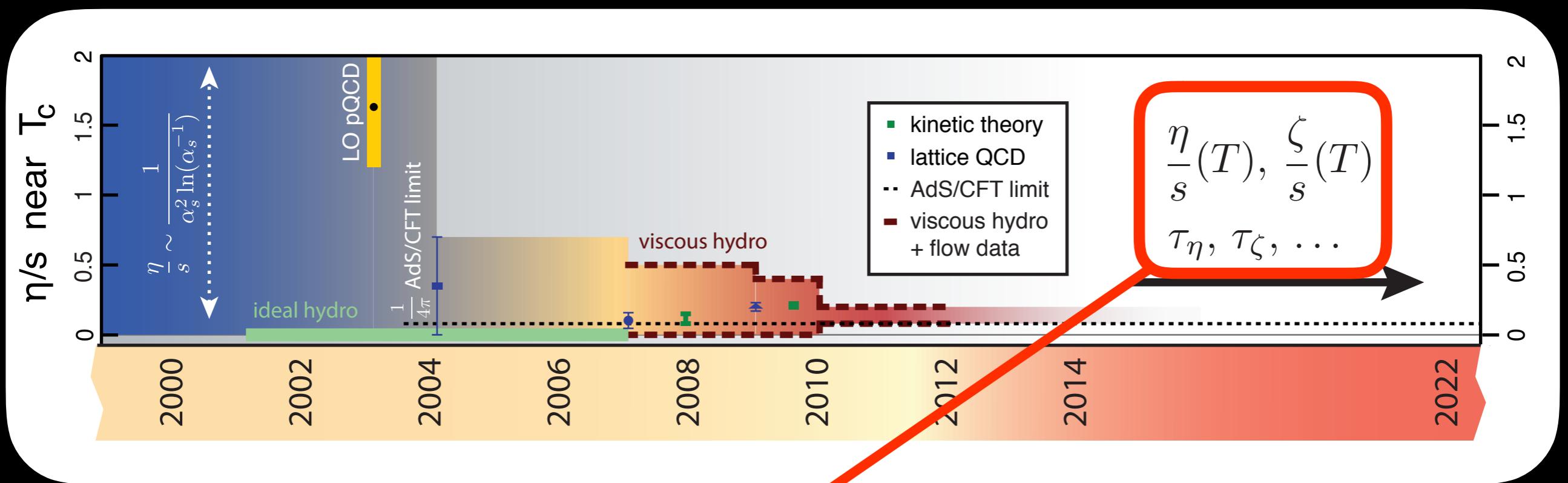
M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915

H. Song, U. W. Heinz, J.Phys. G36 (2009) 064033

H. Song, S. A. Bass, U. Heinz, T. Hirano, C. Shen, Phys.Rev.Lett. 106 (2011) 192301

Improved understanding of QCD shear viscosity

Event-by-event viscous hydrodynamic simulations with QCD based initial states can help extract transport properties



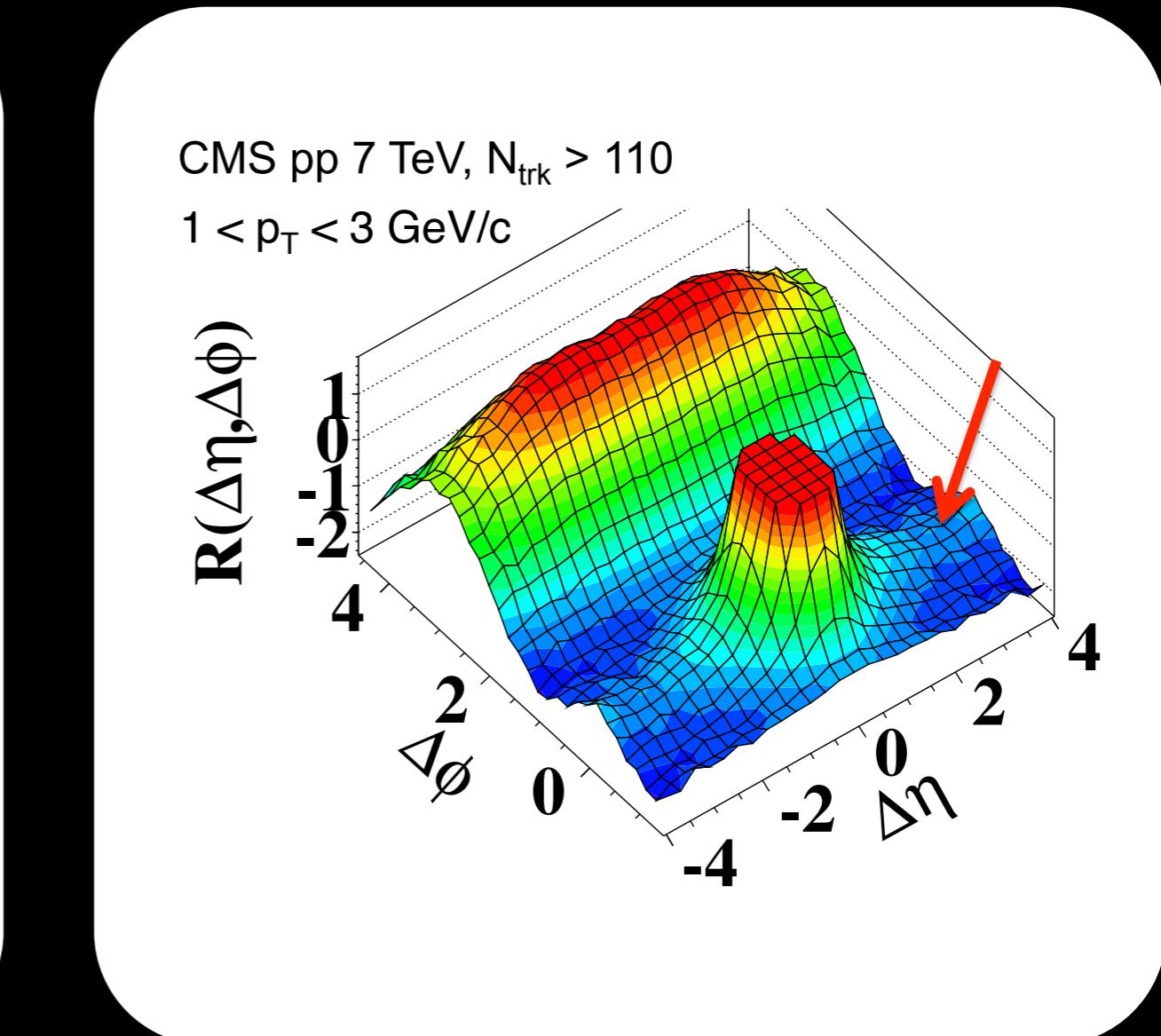
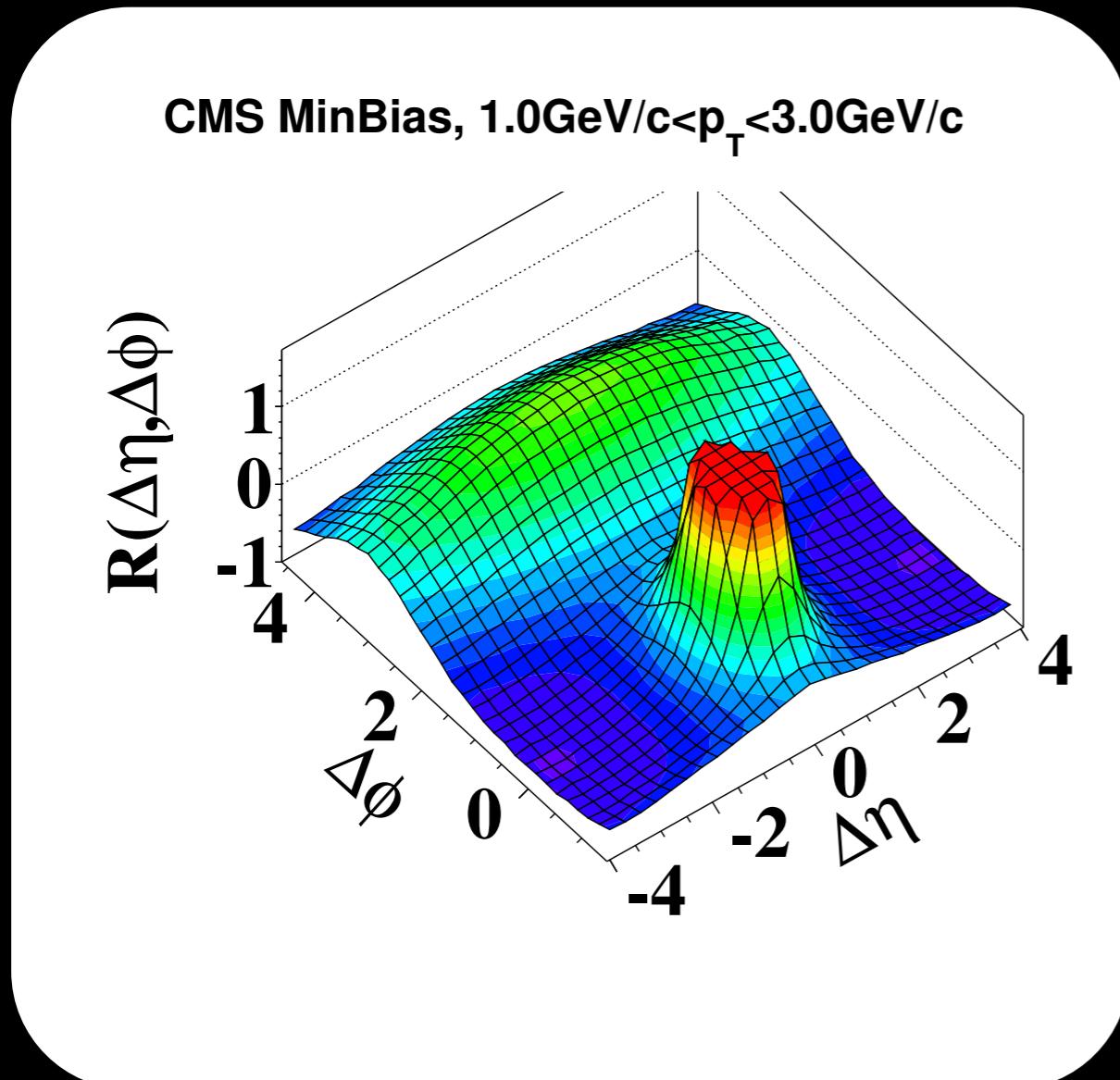
Important progress on these:

- G. Denicol, A. Monnai, B. Schenke, Phys. Rev. Lett. 116, 212301 (2016) Using forward results from RHIC
J.E. Bernhard, J.S. Moreland, S.A. Bass, J. Liu, U. Heinz, Phys. Rev. C94, 024907 (2016) Bayesian analysis
H. Niemi, K.J. Eskola, R. Paatelainen, Phys. Rev. C93, 024907 (2016) EKRT looking at event plane correlations
S. Ryu, J.-F. Paquet, C. Shen, G. S. Denicol, B. Schenke, S. Jeon, and C. Gale, Phys. Rev. Lett. 115, 132301 (2015)
Effect of bulk viscosity
...

Now small systems: proton+proton,
proton/deuteron + heavy ion collisions

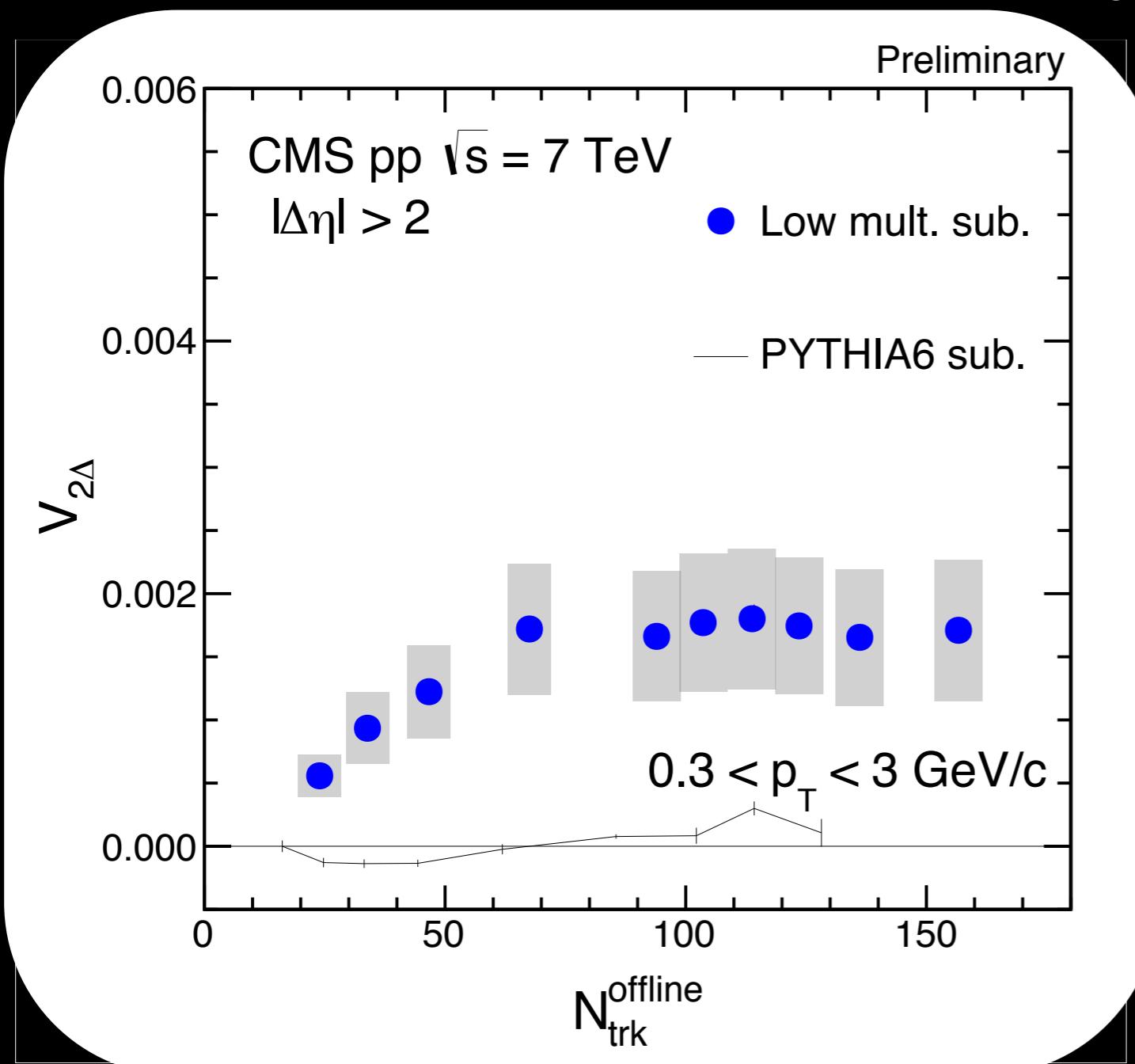
minimum bias p+p

high multiplicity p+p



$V_{2\Delta}$ in p+p collisions

Result after correcting for back-to-back jet correlations
estimated from low multiplicity events

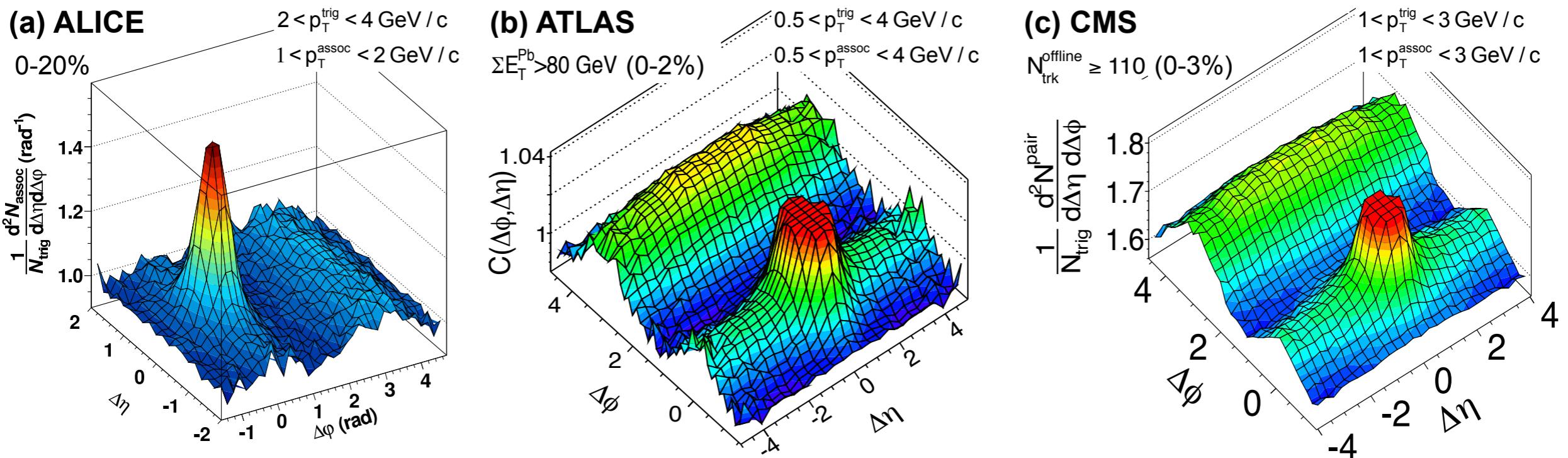


No v_2 in PYTHIA
CMS PAS HIN-15-009

Ridge in p+Pb collisions

high multiplicity p+Pb

pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ at the LHC

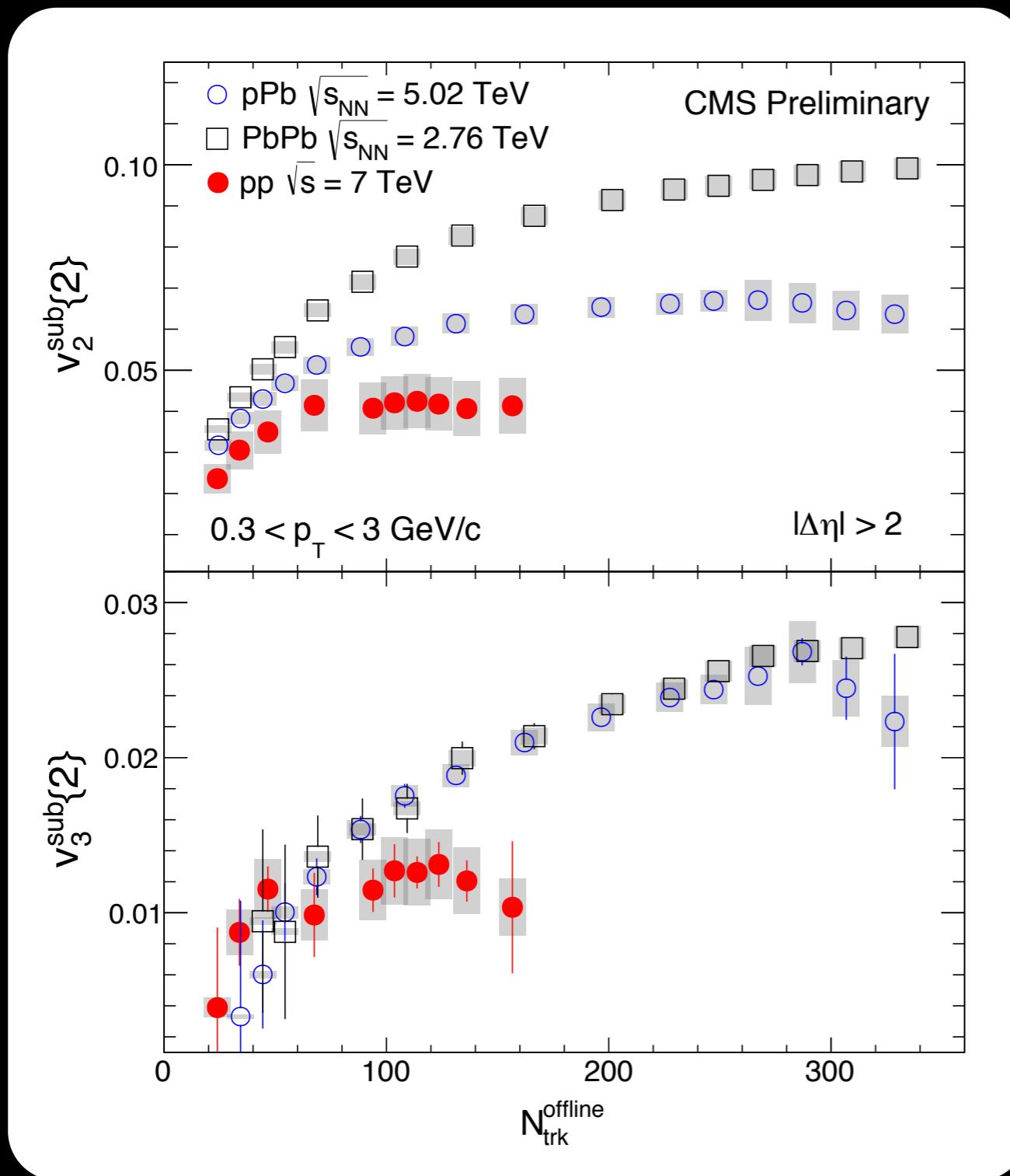


ALICE Collaboration, Phys. Lett. B 719 (2013) 29

ATLAS Collaboration, Phys. Rev. Lett. 110 (2013) 182302

CMS Collaboration, Phys. Lett. B 718 (2013) 795

v_2 in p+p, p+Pb, Pb+Pb collisions



see also:

ALICE Collaboration

Phys. Lett. B719 (2013) 29-41

Phys. Rev. C 90, 054901

ATLAS Collaboration

Phys. Rev. Lett. 110, 182302 (2013); Phys. Rev. C 90.044906 (2014)

CMS Collaboration

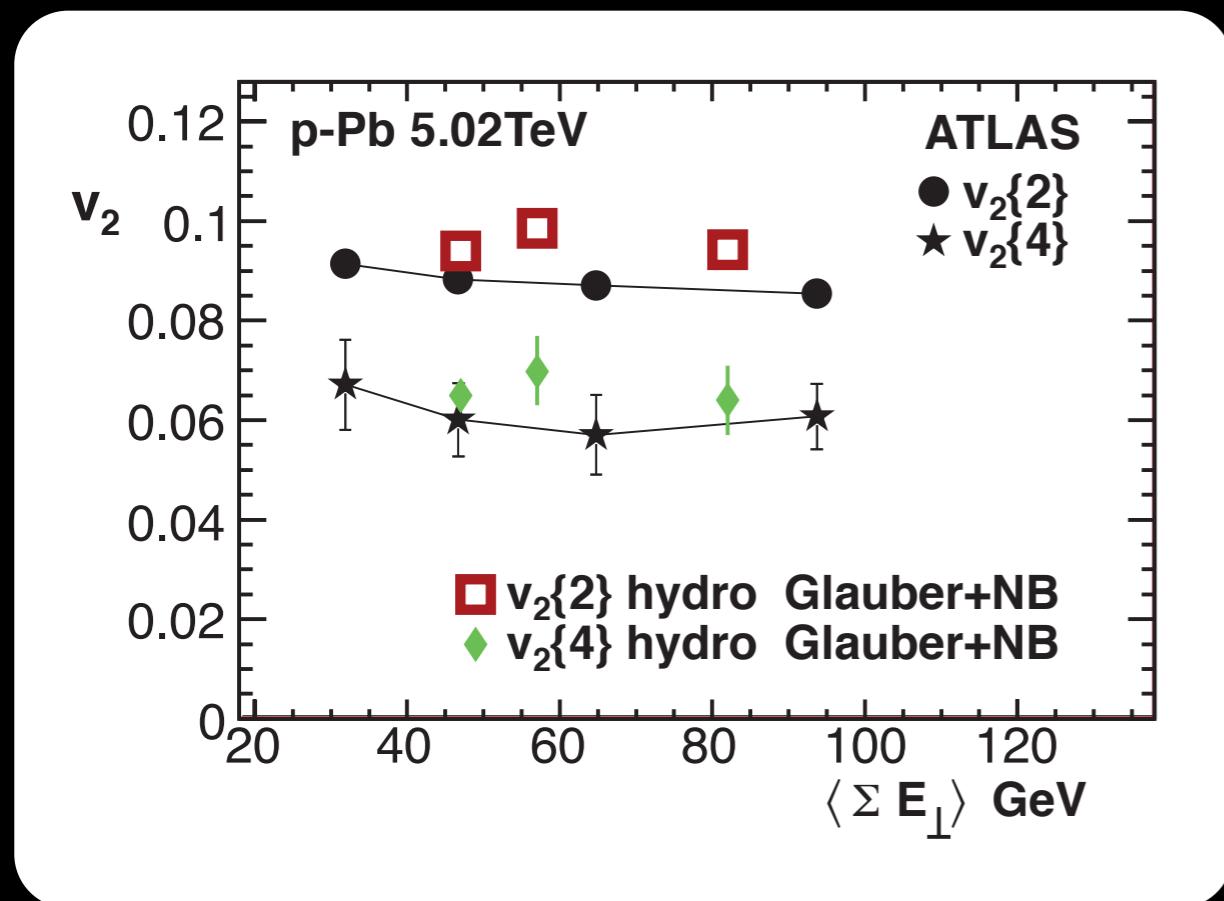
Phys. Rev. Lett. 115, 012301 (2015)



Hydrodynamics in small systems

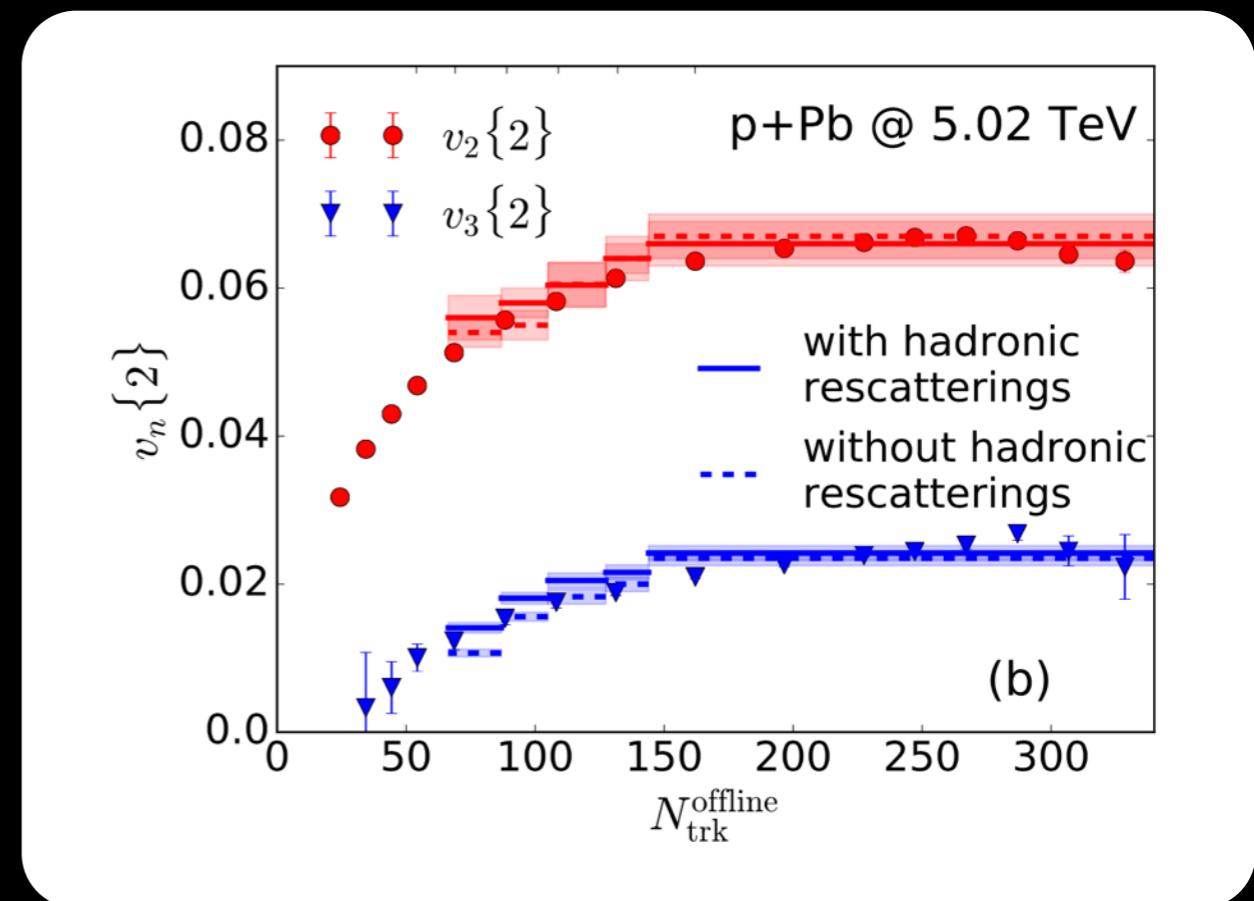
Simple MC-Glauber initial state + hydrodynamics works

ATLAS Coll. PLB725 (2013) 60-78



Bozek, Broniowski, PRC88 (2013) 014903

CMS Coll. PLB724, 213–240 (2013)

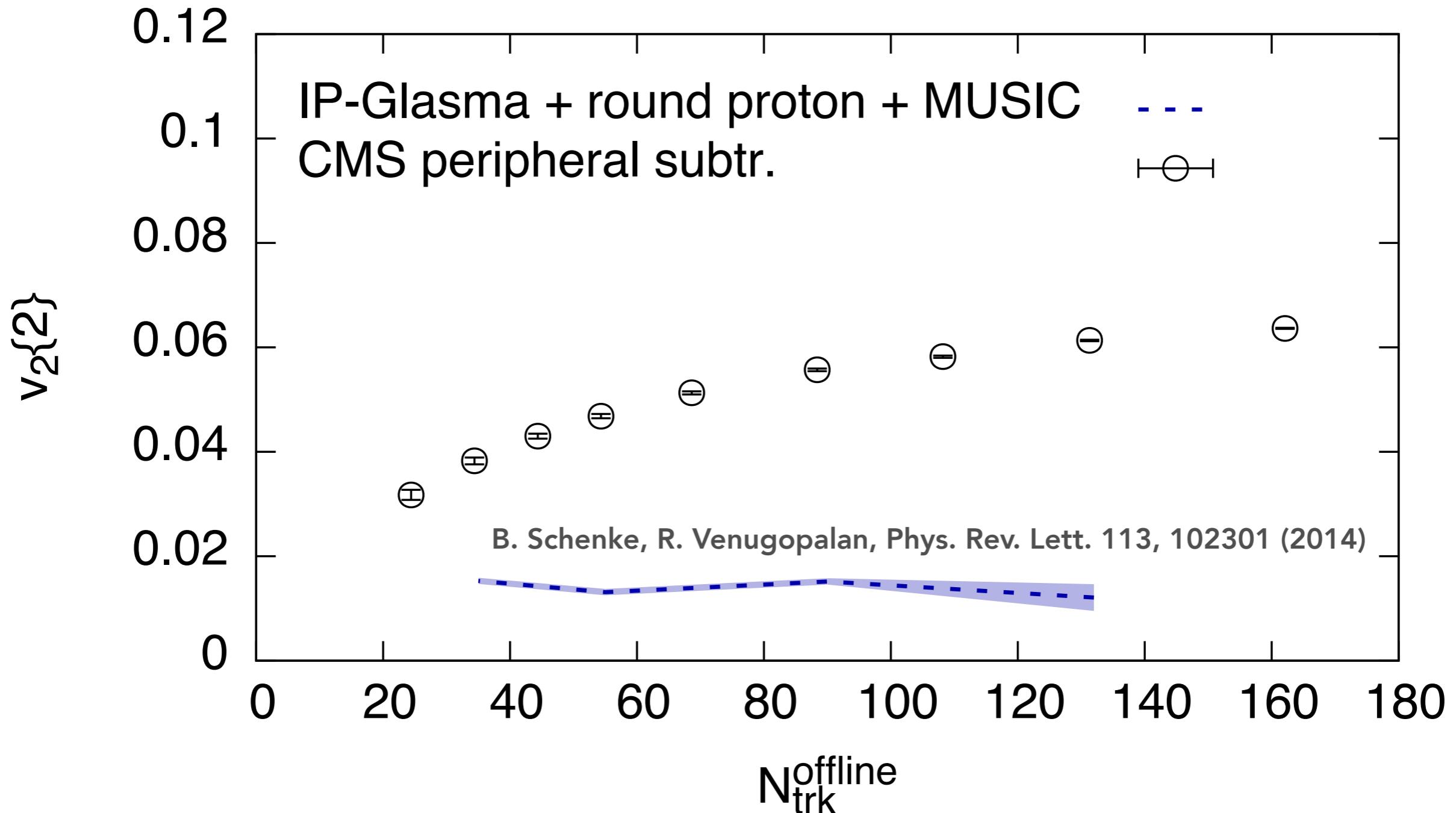


Shen, Paquet, Denicol, Jeon, Gale, PRC95 (2017) 014906

Also see: Kozlov, Luzum, Denicol, Jeon, Gale; Werner, Beicher, Guiot, Karpenko, Pierog; Romatschke; Kalaydzhyan, Shuryak, Zahed; Ghosh, Muhuri, Nayak, Varma; Qin, Mueller; Bozek, Broniowski, Torrieri; Habich, Miller, Romatschke, Xiang; T. Hirano, K. Kawaguchi, K. Murase; ...

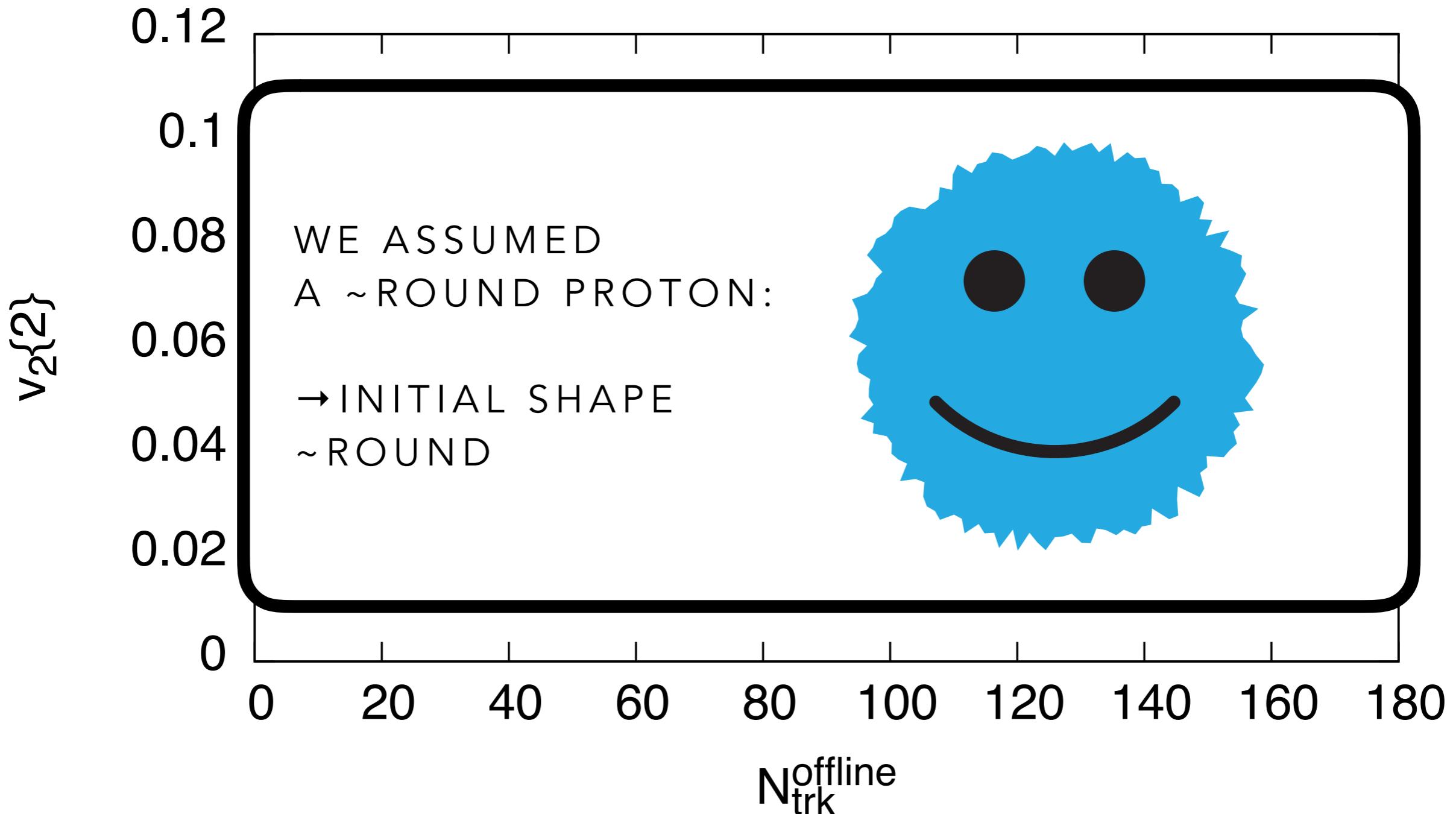
IP-Glasma+MUSIC results

Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)



IP-Glasma+MUSIC results

Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)

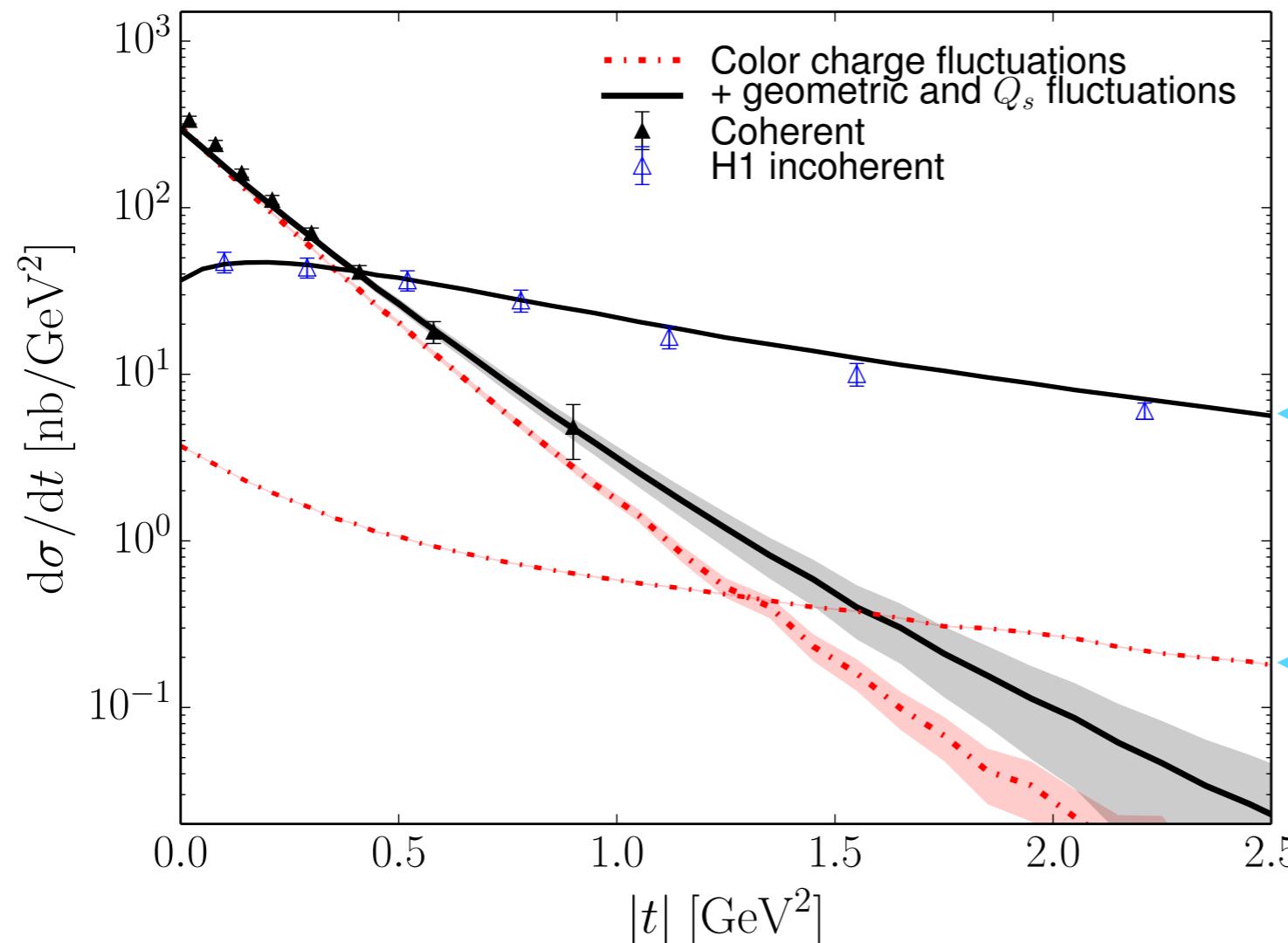
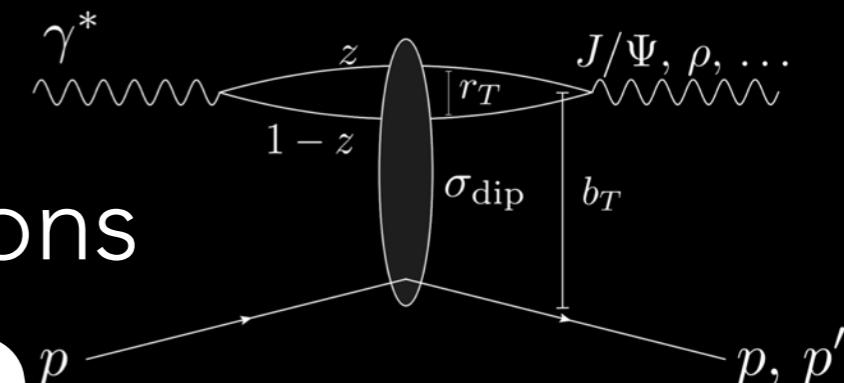


Proton should fluctuate. How much?

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys. Rev. D94 (2016) 034042

Exclusive diffractive J/ Ψ production:

Incoherent x-sec sensitive to fluctuations



tuned shape
fluctuations

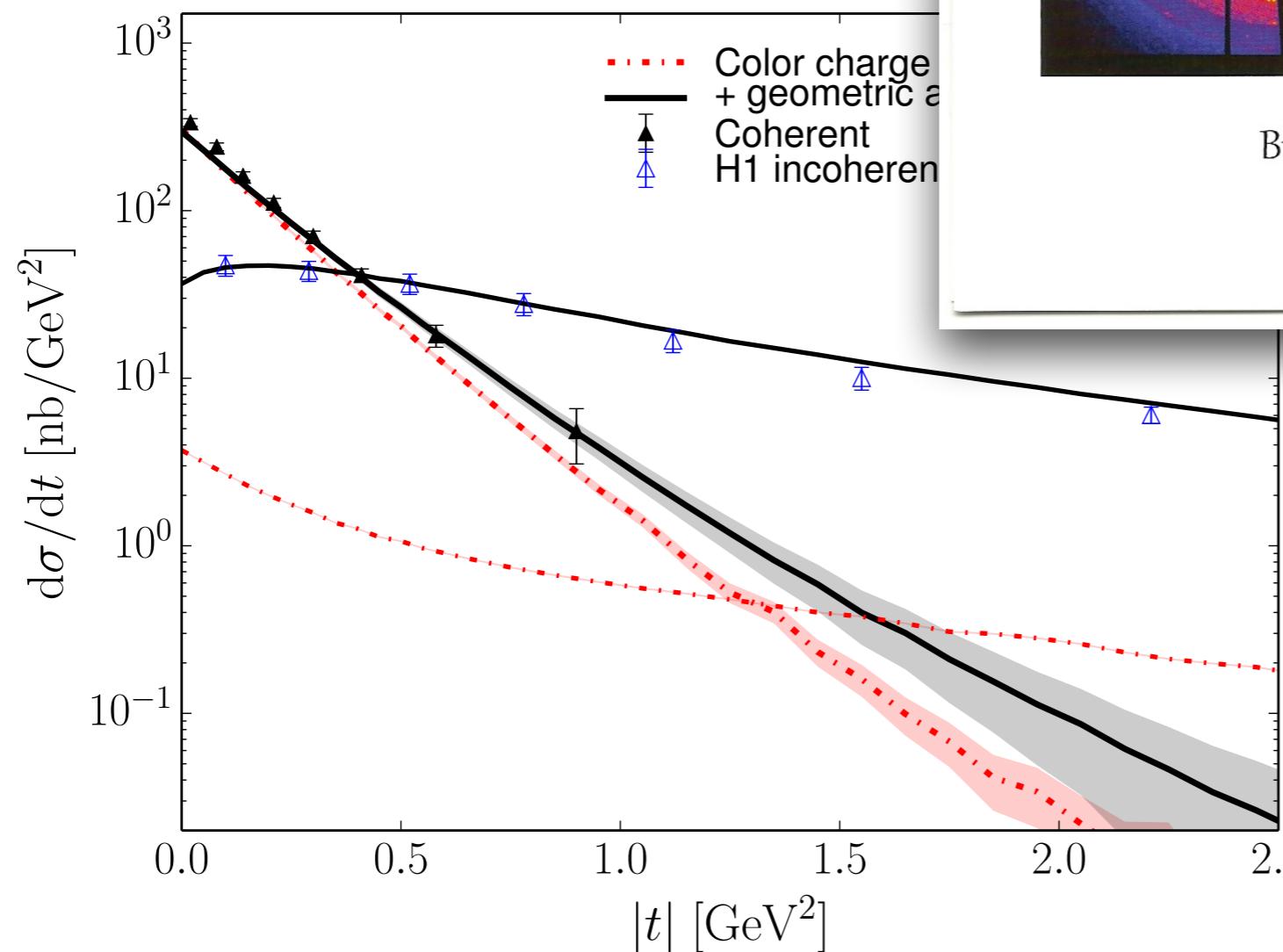
round proton

Proton should fluctuate

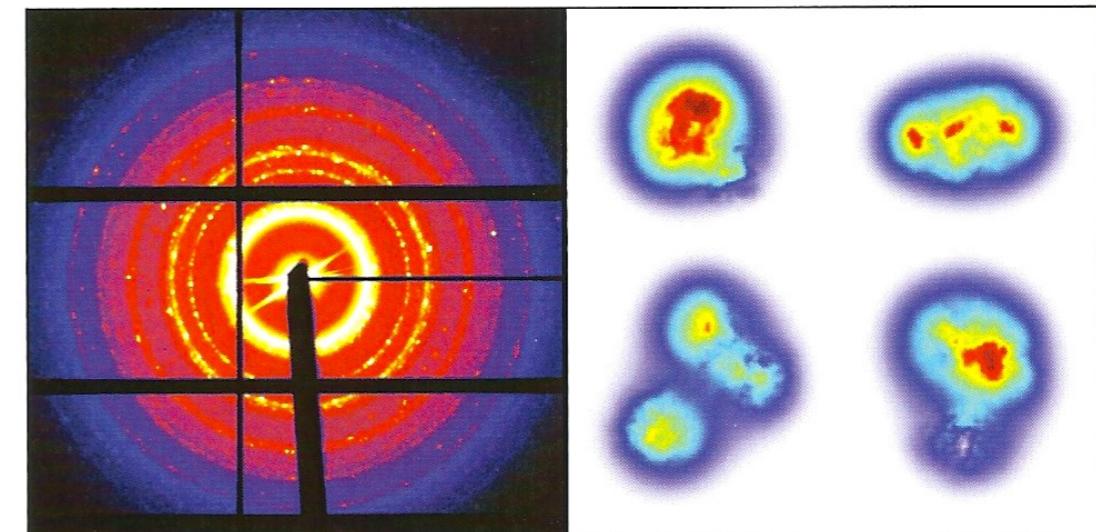
H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016)

Exclusive diffractive J/ Ψ production

Incoherent x-sec sensitive



2016 Holiday Card



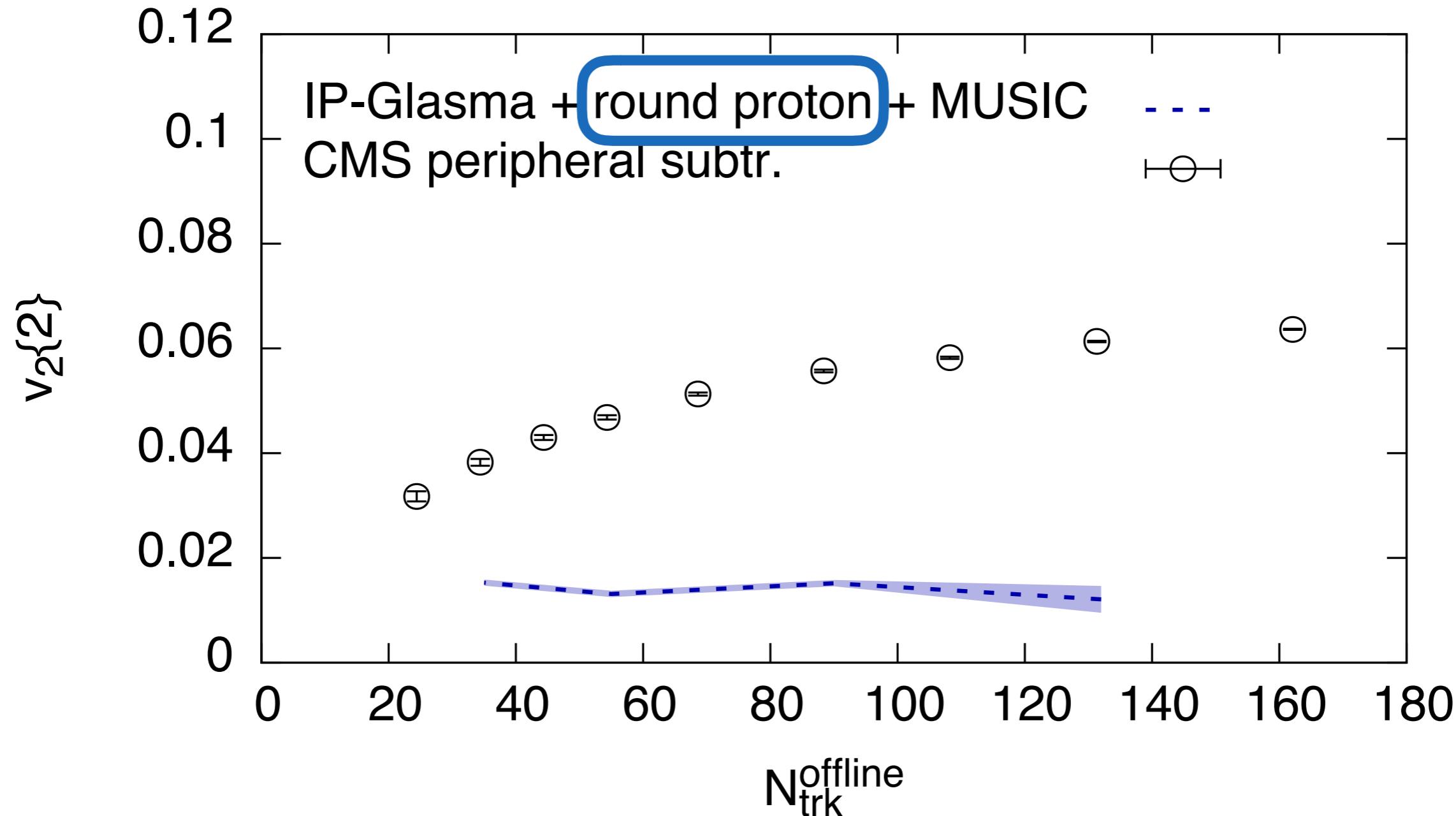
Brookhaven National Laboratory

tuned shape
fluctuations

round proton

Let's compare to data again...

B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)

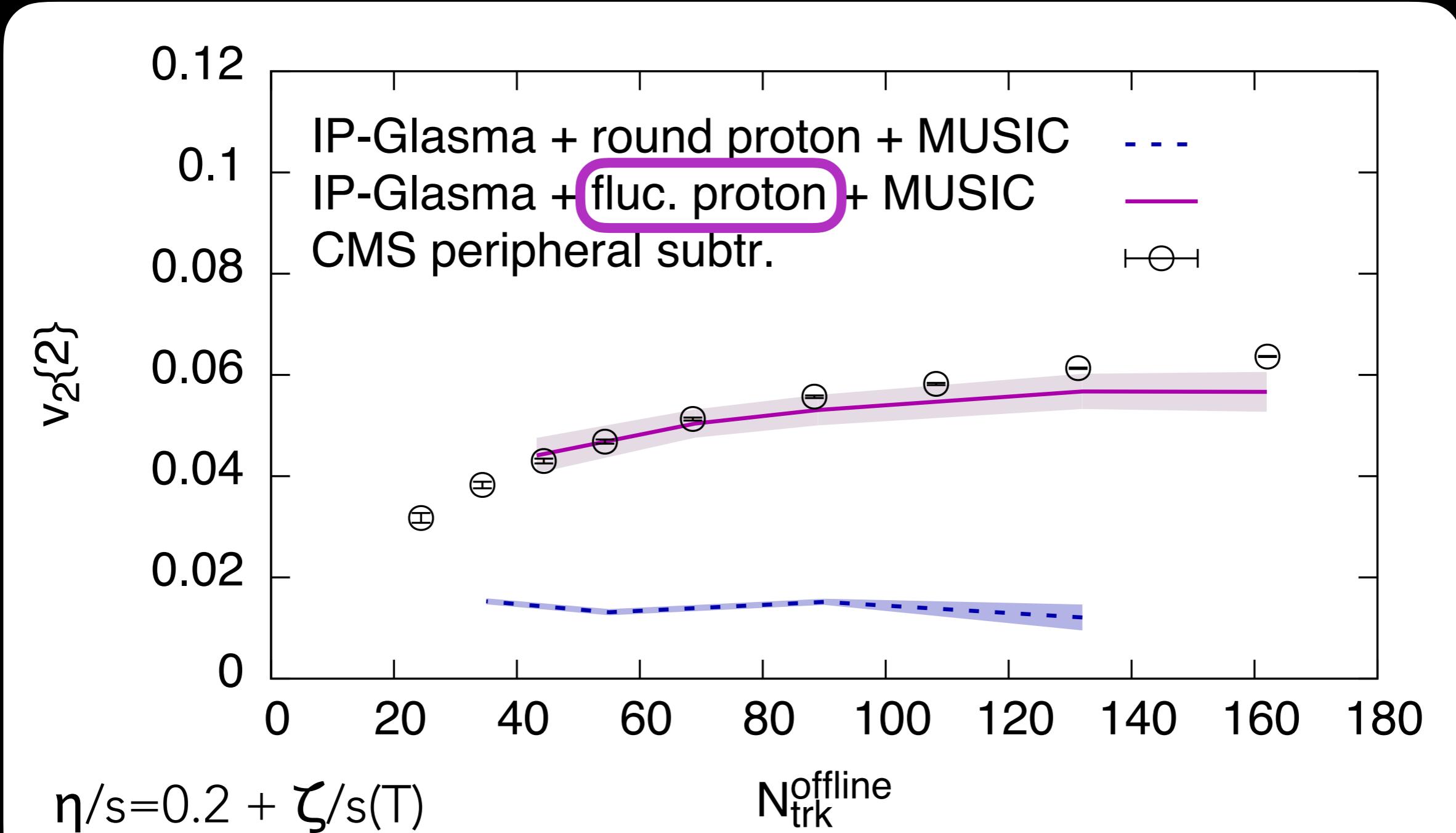


Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)

Effect of proton shape fluctuations

B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)

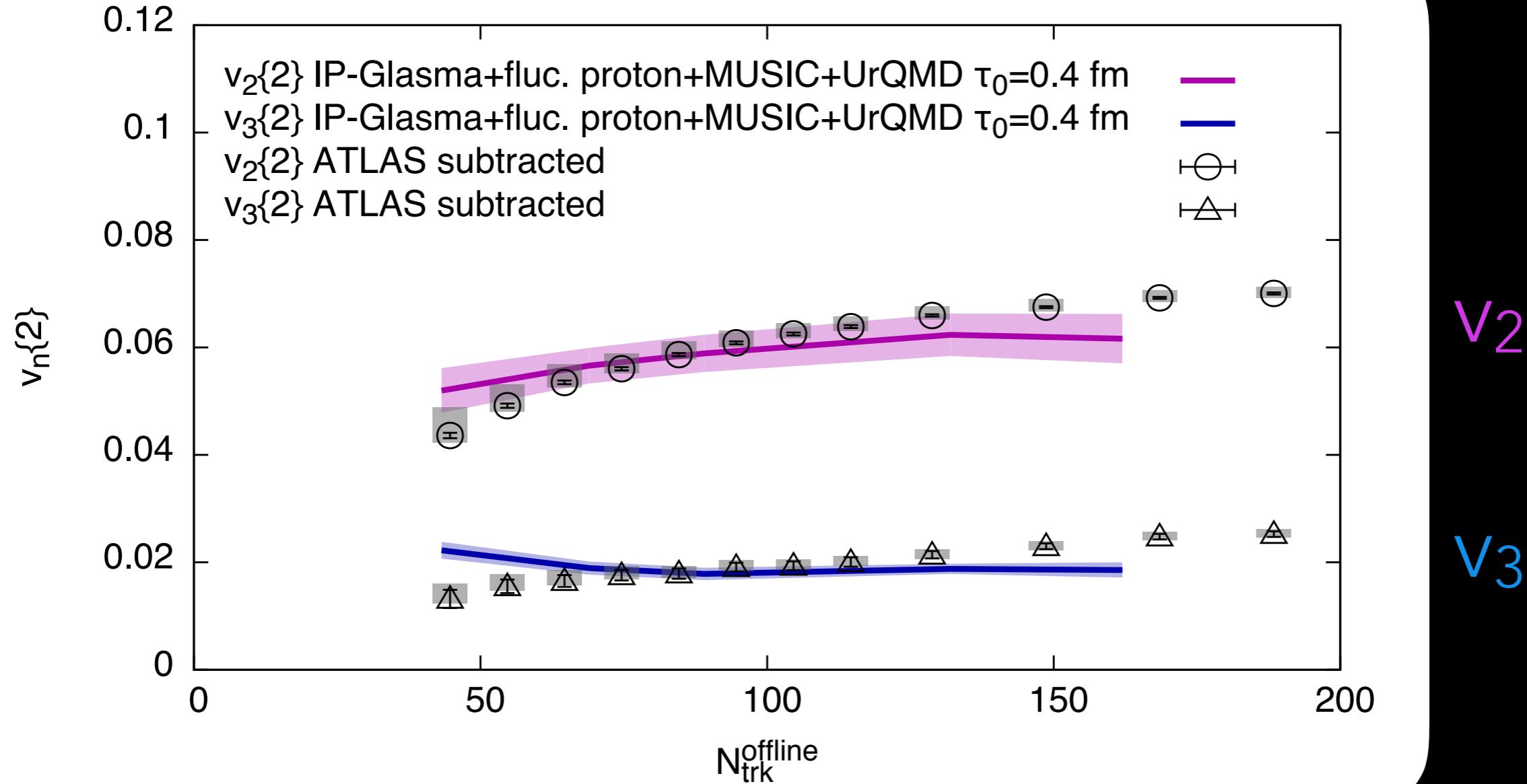
H. Mäntysaari, P. Tribedy, B. Schenke, C. Shen, in preparation (2017)



Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)

Elliptic and triangular flow

H. Mäntysaari, P. Tribedy, B. Schenke, C. Shen, in preparation (2017)

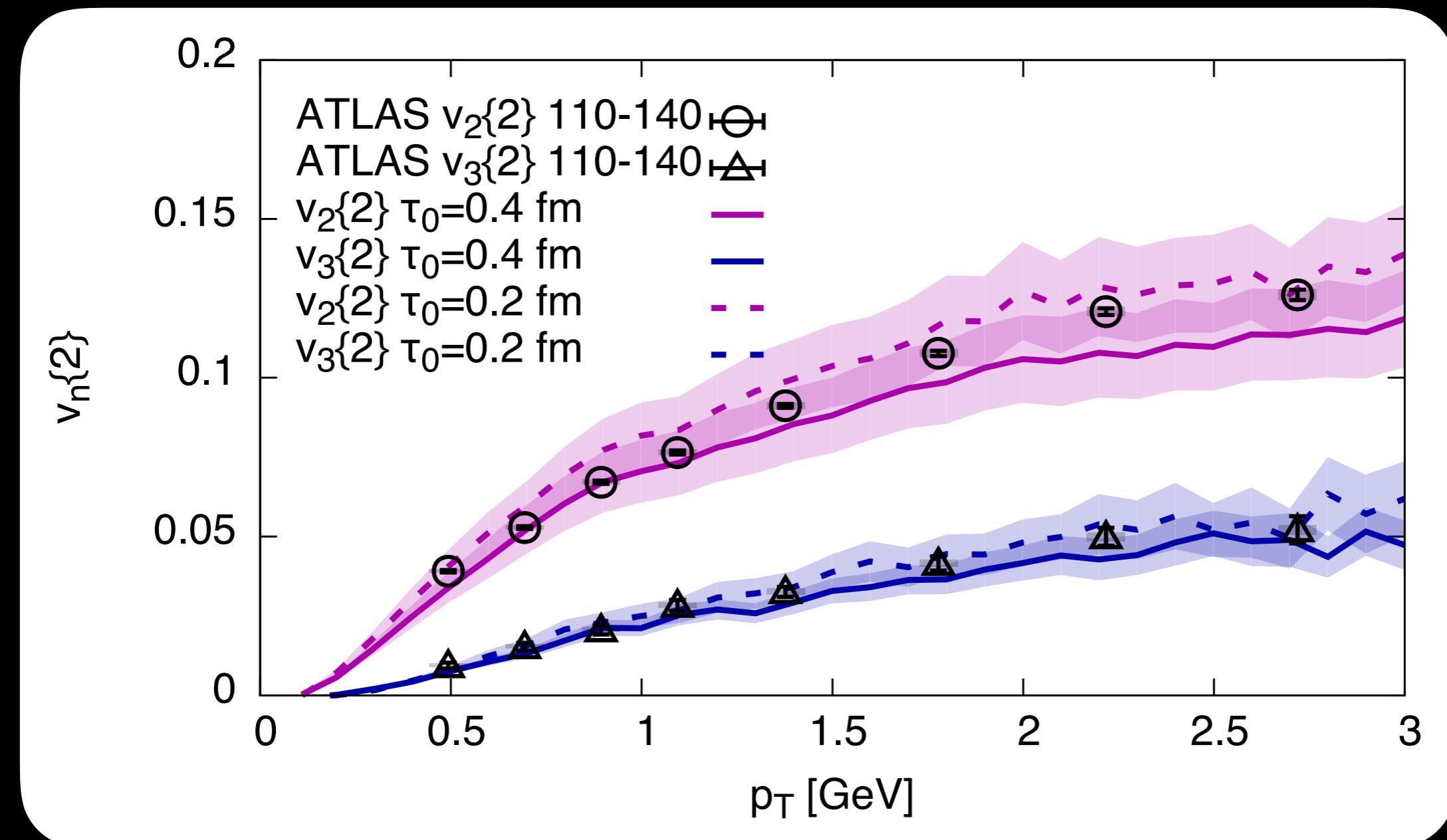


ATLAS Collaboration, Phys.Rev. C90 (2014) 044906

$$\eta/s = 0.2 + \zeta/s(T)$$

Transverse momentum dependence

H. Mäntysaari, P. Tribedy, B. Schenke, C. Shen, in preparation (2017)

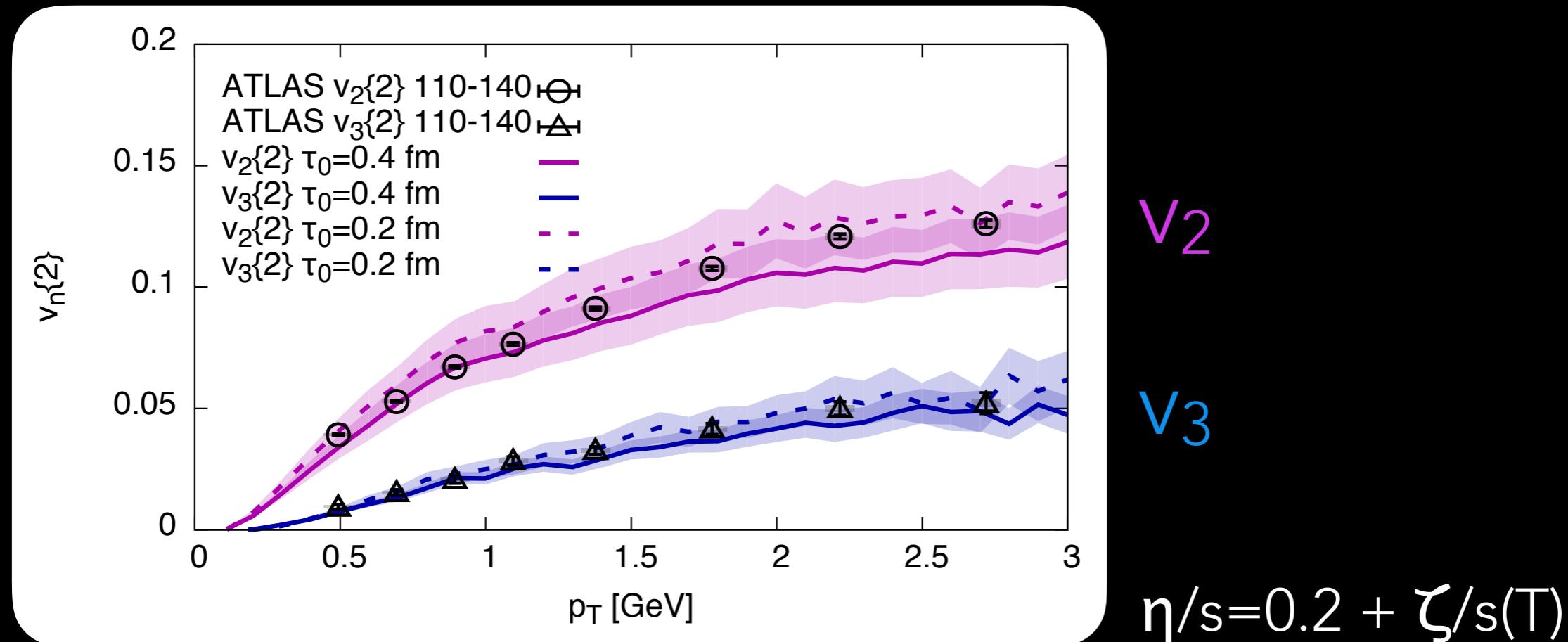


ATLAS Collaboration, Phys.Rev. C90 (2014) 044906

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Transverse momentum dependence

H. Mäntysaari, P. Tribedy, B. Schenke, C. Shen, in preparation (2017)

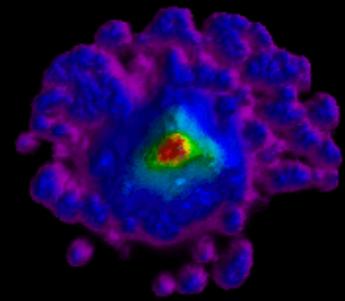


ATLAS Collaboration, Phys.Rev. C90 (2014) 044906

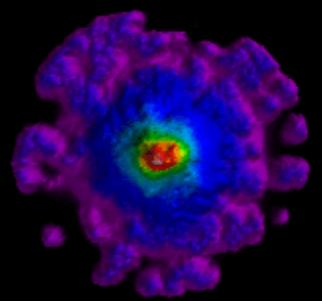
Fair warning: Strong dependence on whether initial shear stress tensor is included and the relaxation time. Viscous corrections can be very large

Temperature profile without bulk viscosity

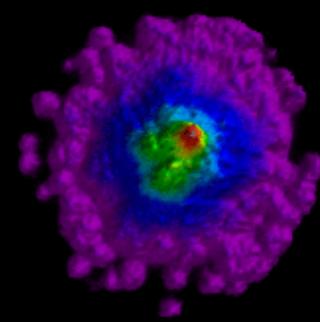
$\sim 1\langle N \rangle$



$\sim 2\langle N \rangle$

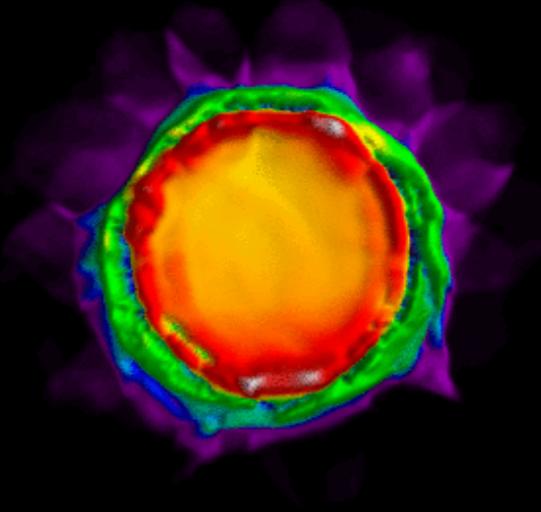


$\sim 3\langle N \rangle$

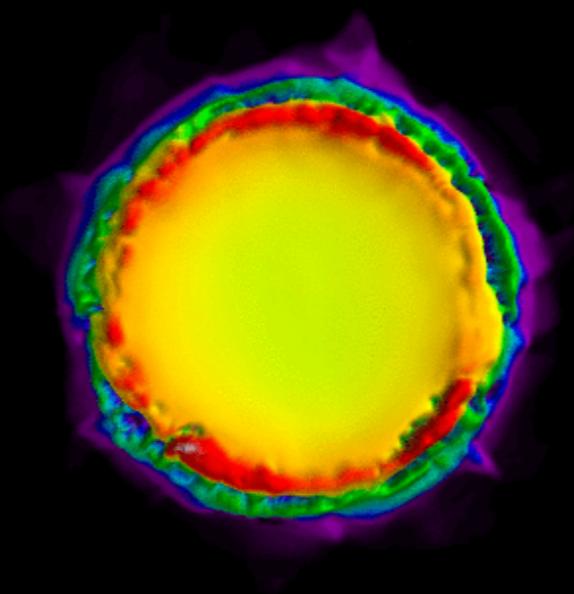


Temperature profile without bulk viscosity

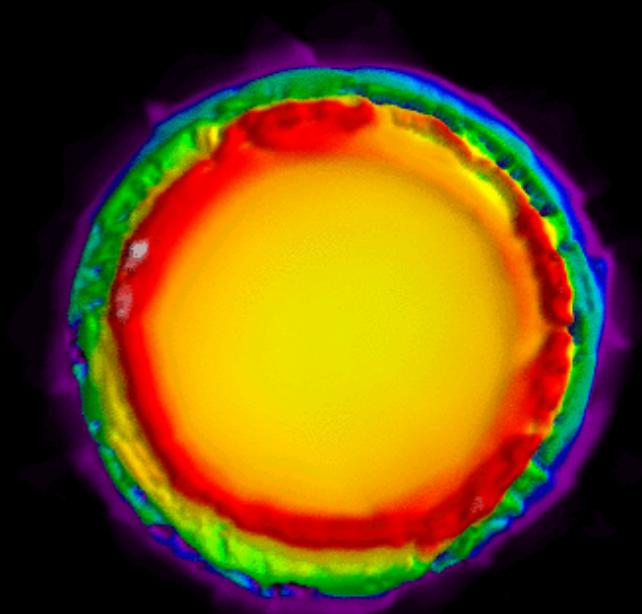
$\sim 1\langle N \rangle$



$\sim 2\langle N \rangle$



$\sim 3\langle N \rangle$



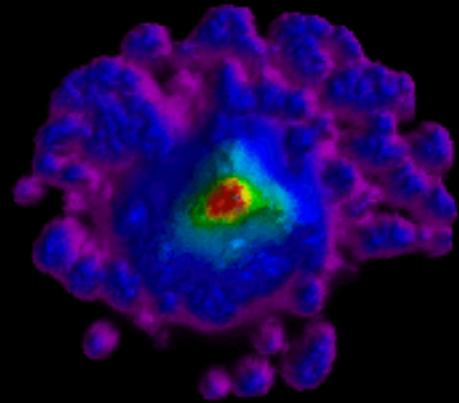
2.55 fm

3.6 fm

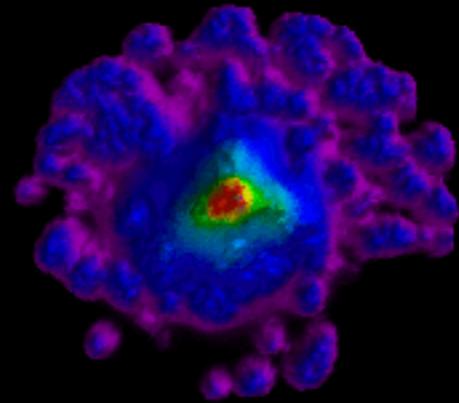
4.2 fm

Effect of Bulk viscosity

w/o bulk viscosity

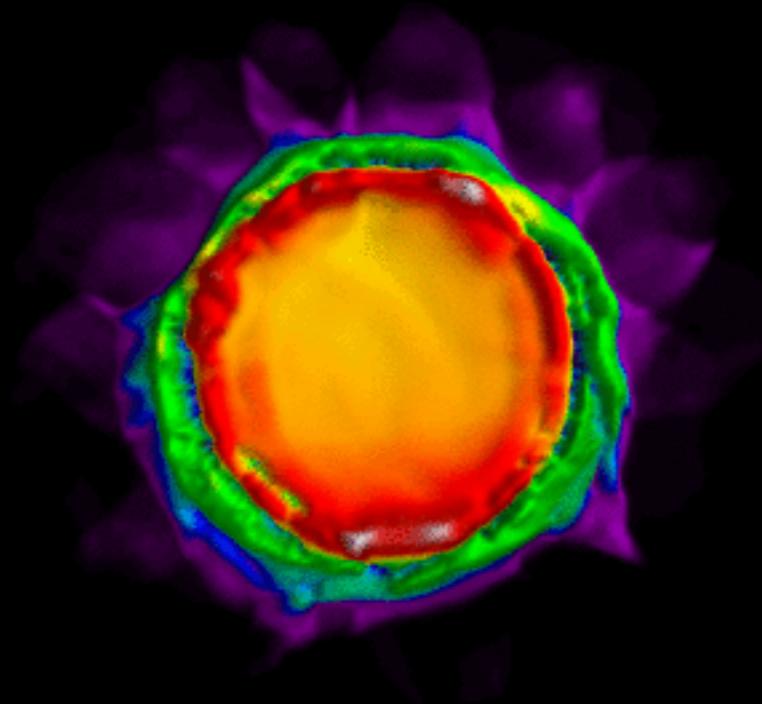


with bulk viscosity



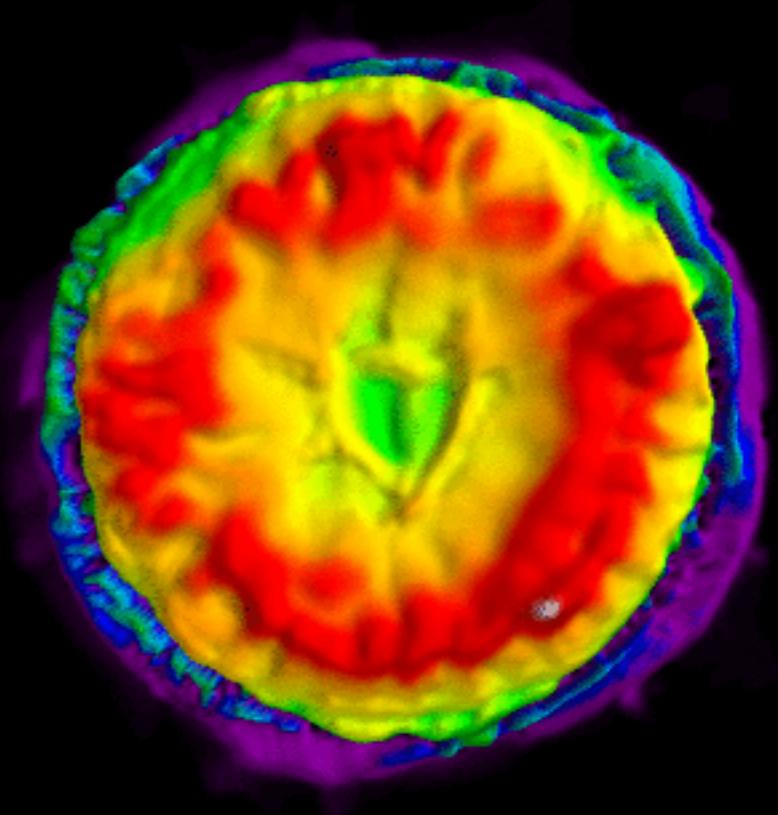
Effect of Bulk viscosity

w/o bulk viscosity



2.55 fm

with bulk viscosity

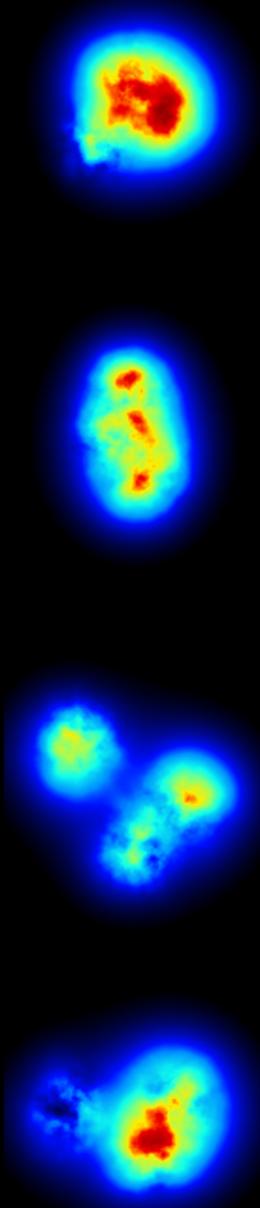


4.65 fm

Success?

Fluctuating proton + IP-Glasma + MUSIC hydro can describe observations in p+A collisions well

We are sensitive to the shape of the proton and its fluctuations: Study of v_n distributions in p+A collisions almost like snapping pictures of individual proton shape configurations



Main caveat is the applicability of hydro:
Non-equilibrium corrections (at $p_T > 1 \text{ GeV}$) are large.
Effective pressure can become negative.
Does not mean what we see is not a final state effect

Initial state correlations

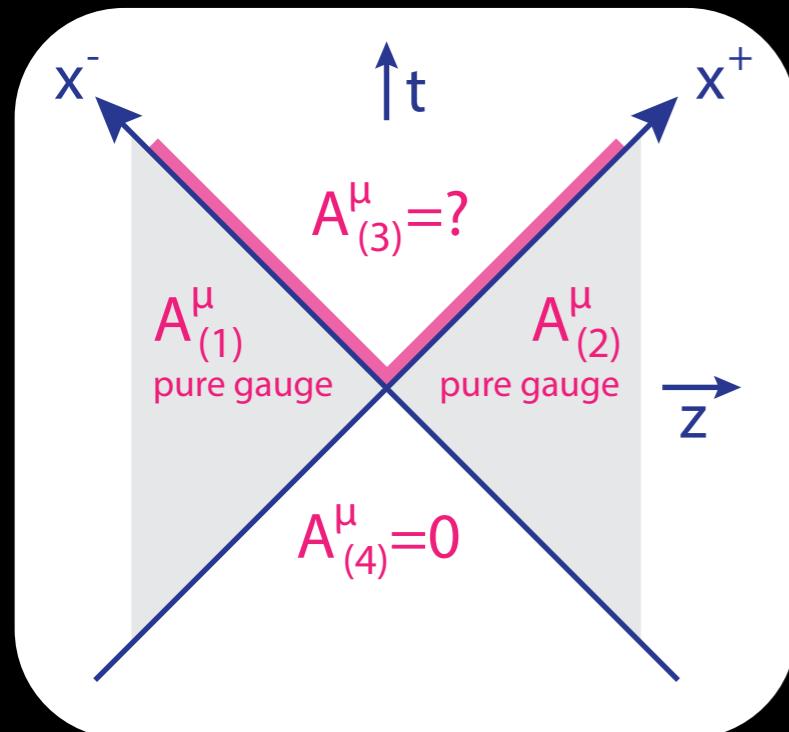


... and now for something completely different

So far we have neglected initial momentum space correlations that are present already in the initial gluon fields

They also lead to non-zero “flow”-harmonics

Backing up to the calculation of initial gluon fields



$$A_{(3)}^i|_{\tau=0^+} = A_{(1)}^i + A_{(2)}^i$$
$$A_{(3)}^\eta|_{\tau=0^+} = \frac{ig}{2} [A_{(1)}^i, A_{(2)}^i]$$

Now compute gluon momentum distributions from the fields in Coulomb gauge

Next we analyze the momentum distribution of the produced gluons

There is NO hydrodynamics in what follows, just Yang-Mills

Correlations from the initial state

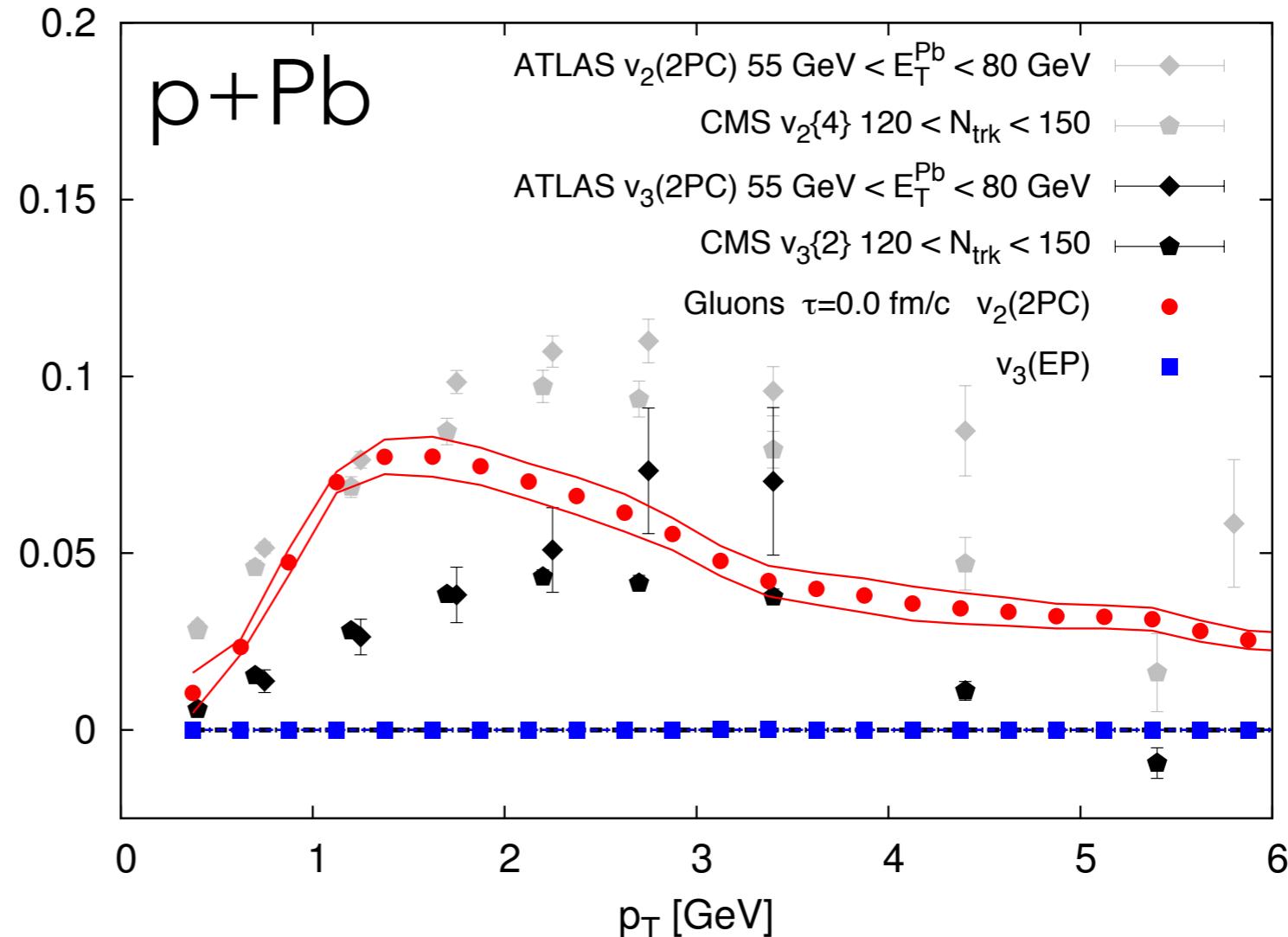
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

$\tau = 0.0 \text{ fm/c}$

gluons

$v_2 \, v_3$

Fourier harmonics (*event average*)



Significant v_2 at time 0

No odd harmonics for gluons without final state interactions

Correlations from the initial state

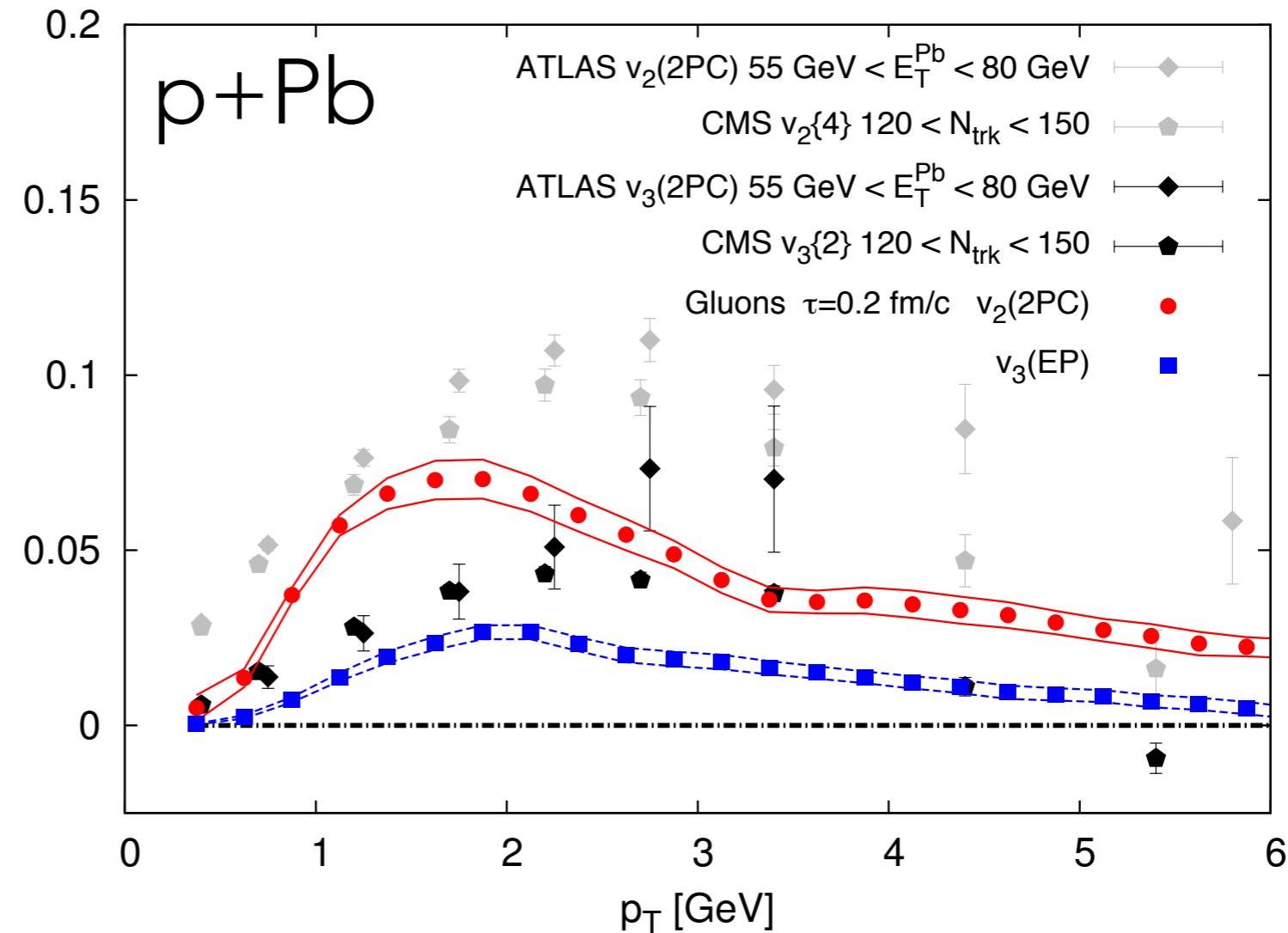
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

$\tau = 0.2 \text{ fm}/c$

gluons

$v_2 v_3$

Fourier harmonics (*event average*)



Correlations from the initial state

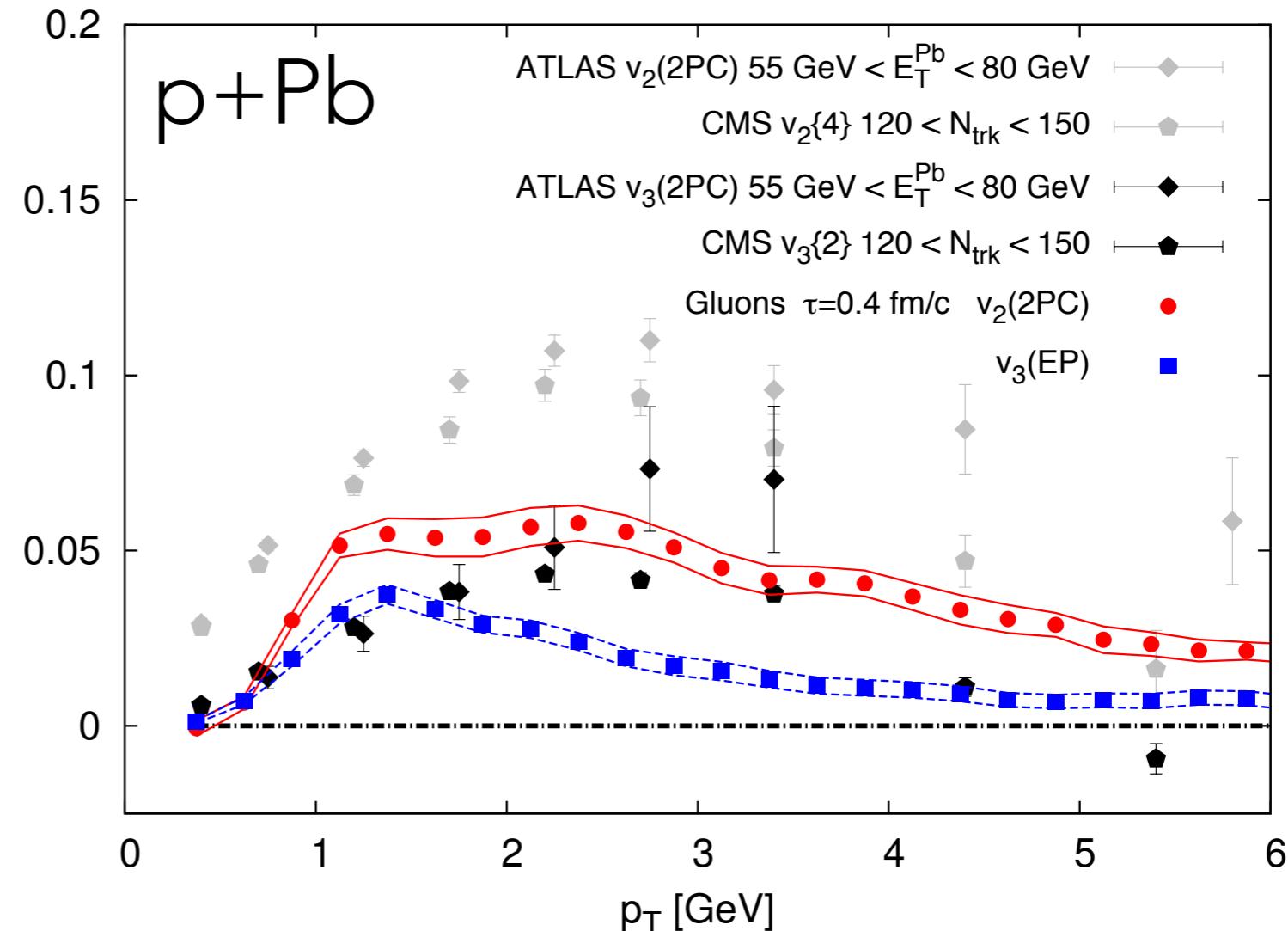
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

$\tau = 0.4 \text{ fm}/c$

gluons

$v_2 v_3$

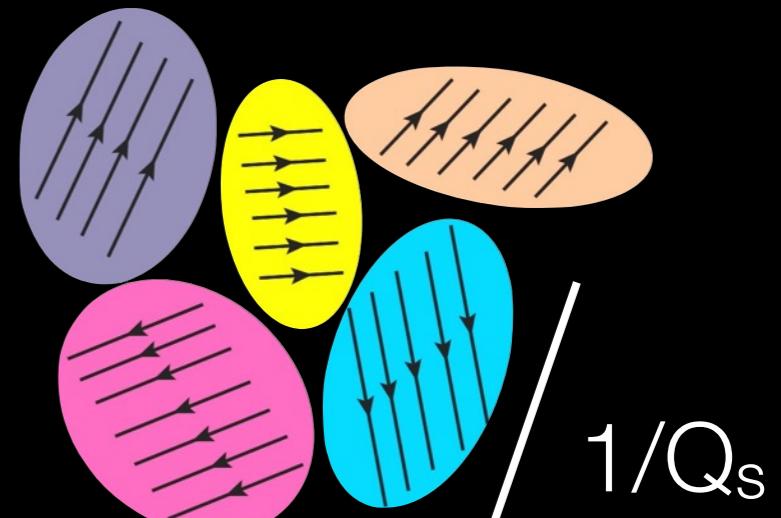
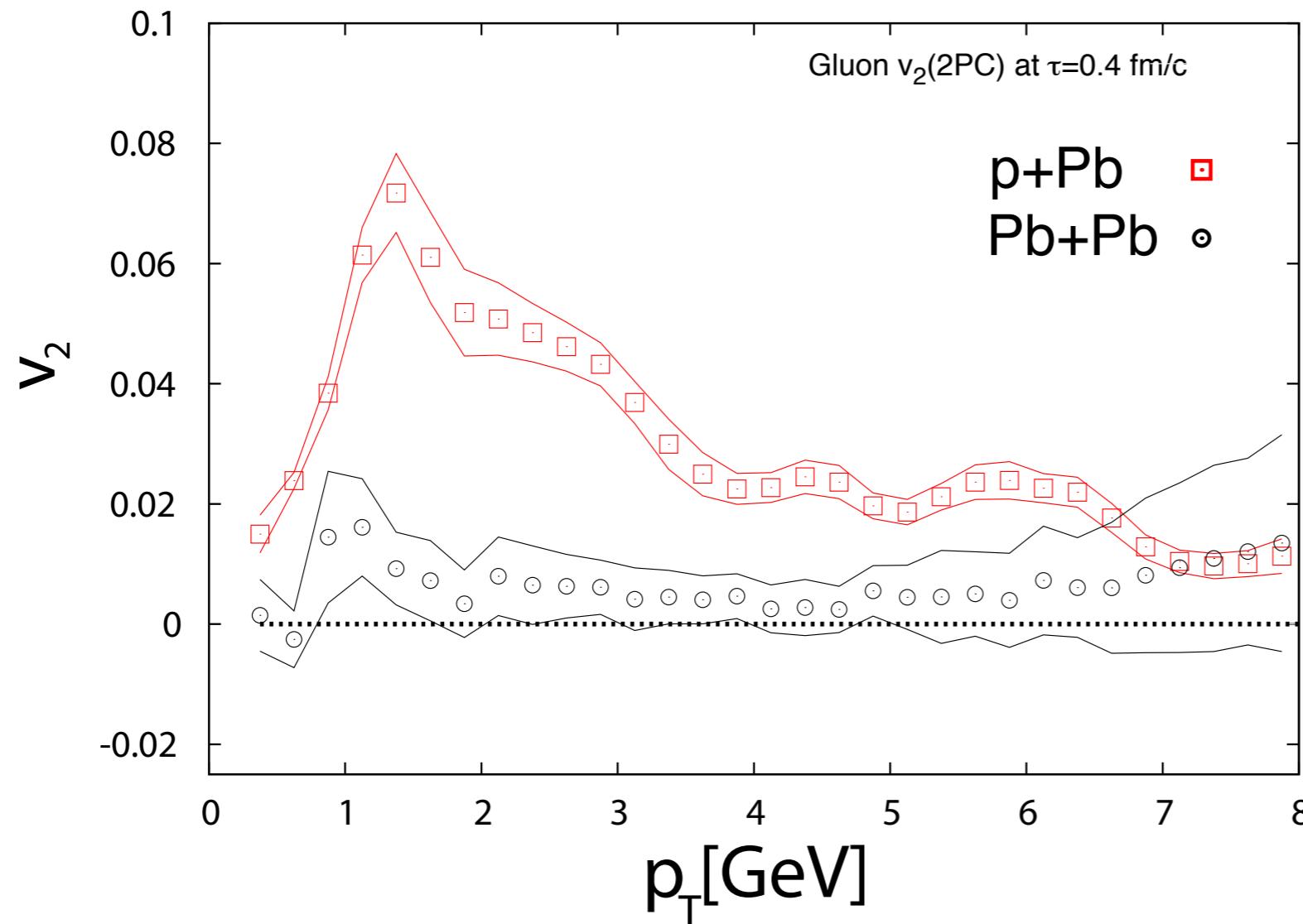
Fourier harmonics (*event average*)



Odd harmonics generated by pre-equilibrium dynamics

Interpretation and system size dependence

Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)



Pb+Pb not described in initial state picture. Reason:
Gluons produced from many uncorrelated color field domains
Collective flow in the final state is needed

Many calculations, different approximations

- **Glasma graph approximation:** only two gluon exchange and Gaussian statistics of color charge fluctuations
- **Non-linear Gaussian approximation:** Multi-gluon exchanges and Gaussian statistics
- **Numerical solution:** Solves Yang-Mills equations exactly as we did, includes multiple-gluon exchange, “rescattering”
- Some go beyond classical approximation by including **JIMWLK** evolution which will introduce some non-Gaussian correlations

They all find anisotropies without any hydrodynamics

Some are compared in

[T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 \(2016\) 061](#)

See the review article

[K. Dusling, W. Li, B. Schenke, Int. J. Mod. Phys. E25, 1630002 \(2016\)](#)

So what do we see?

1. Initial momentum correlations
- or
2. A reflection of the initial geometry
mediated by final state effects?

Observables to tell the difference

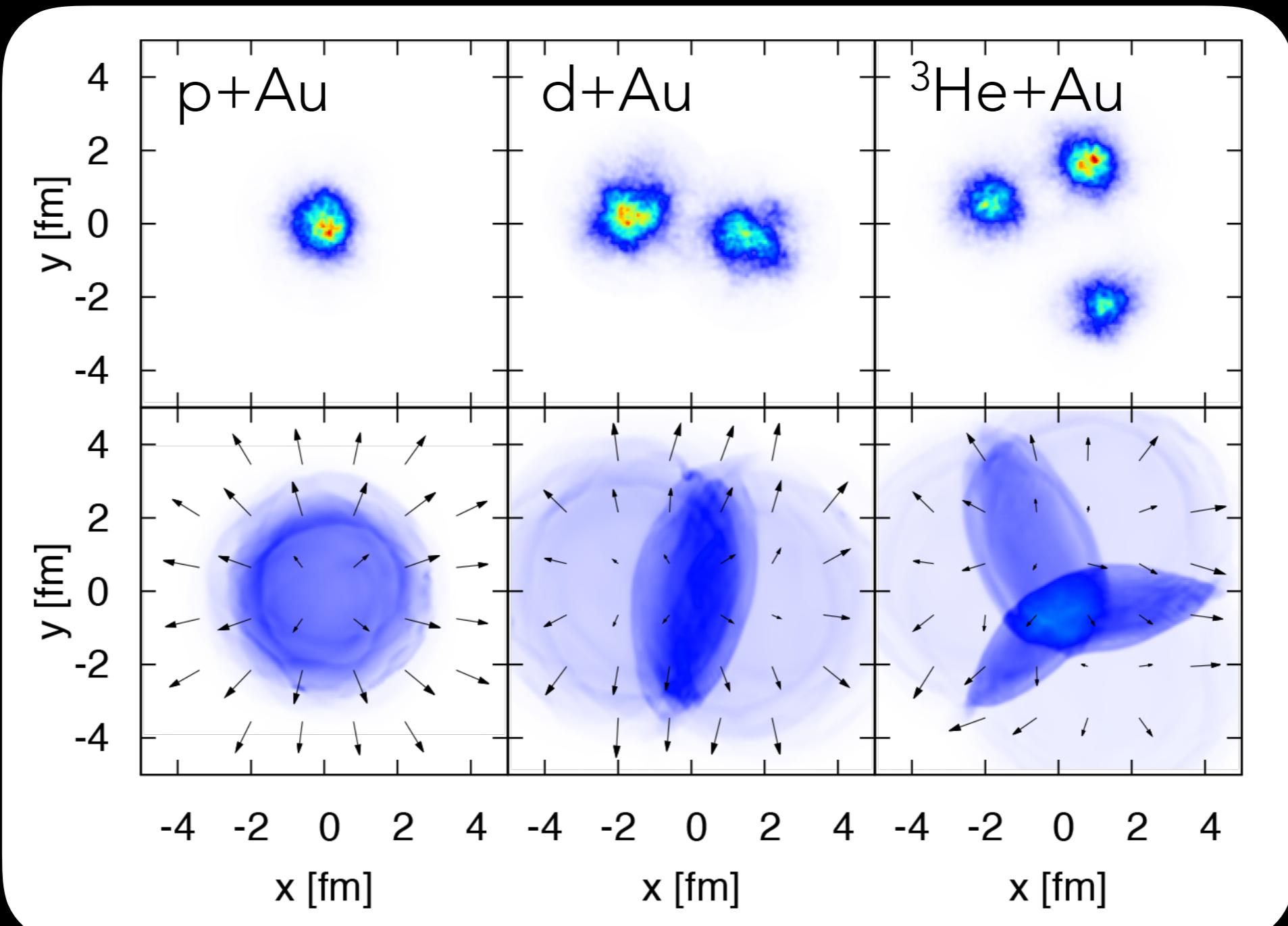
- Different collision systems
- Mass ordering
- Odd harmonics
- Beam energy dependence
- Jet quenching
- Electromagnetic probes
- Sign change of $c_2\{4\}$
- Multi particle (>2) cumulants

Observables to tell the difference

- Different collision systems
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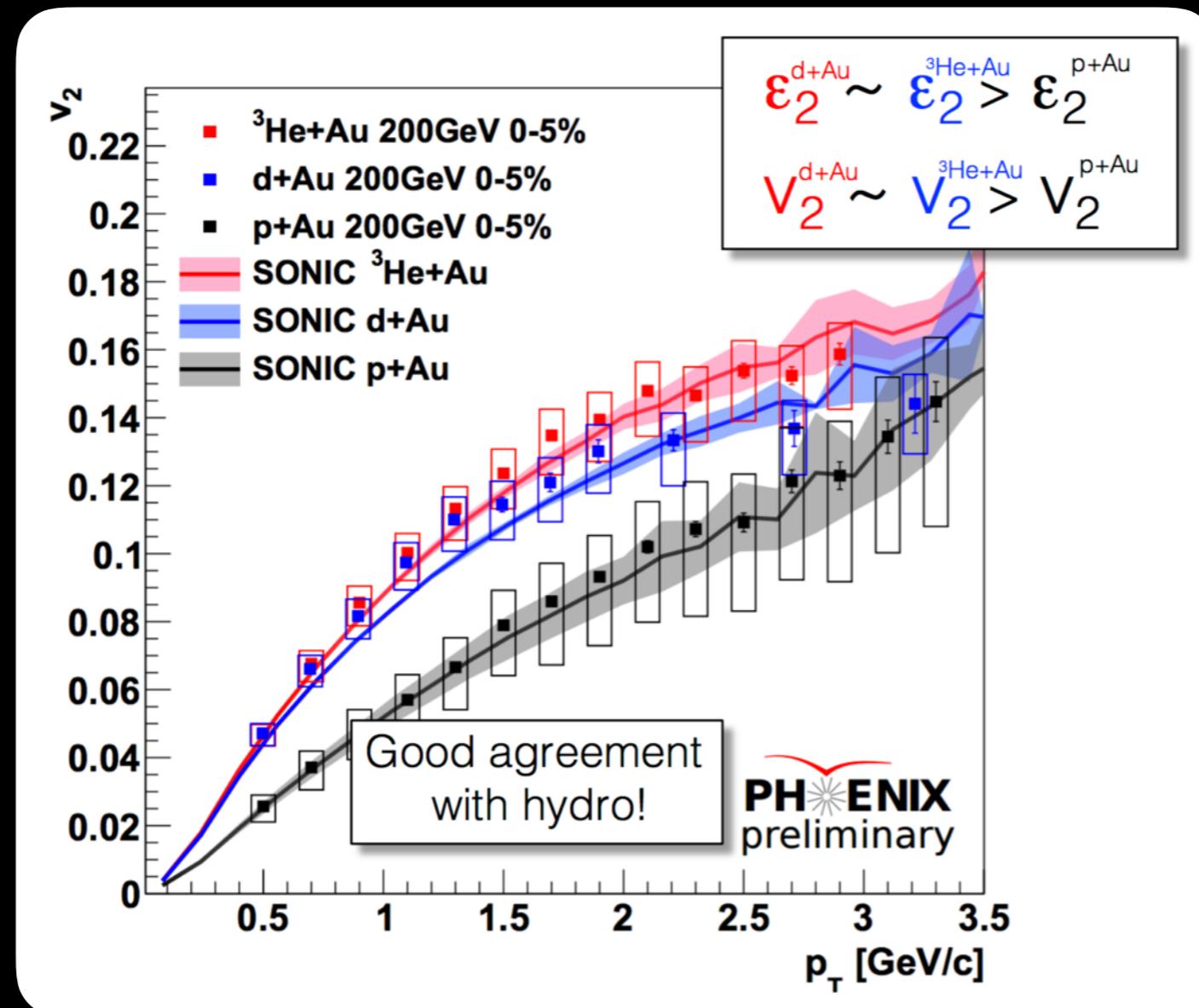
RHIC to the rescue: Different small systems

Different initial shapes lead to different flow harmonics



Different small systems

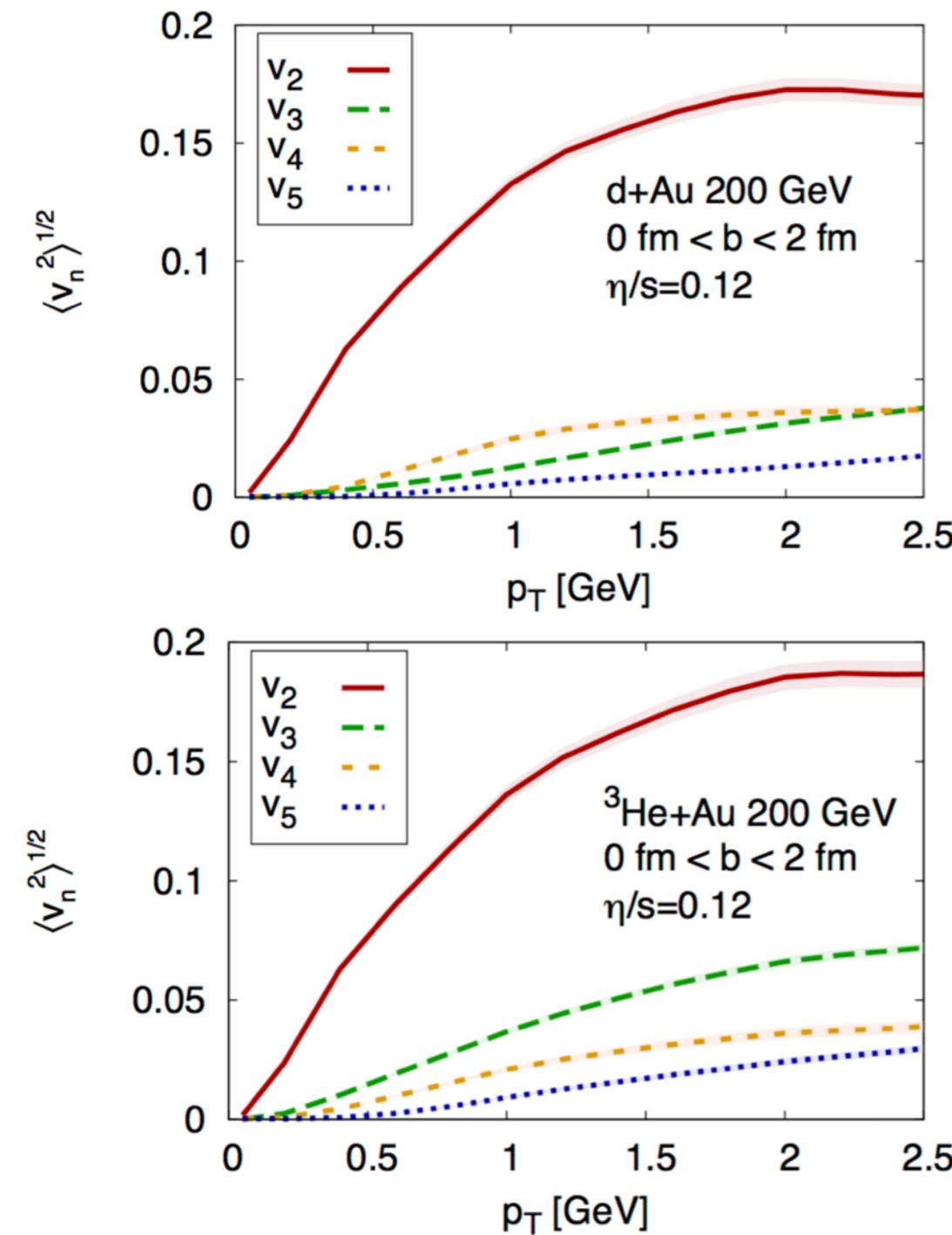
Different initial shapes lead to different flow harmonics



from Javier Orjuela-Koop
for the PHENIX Collaboration
at Initial Stages 2016

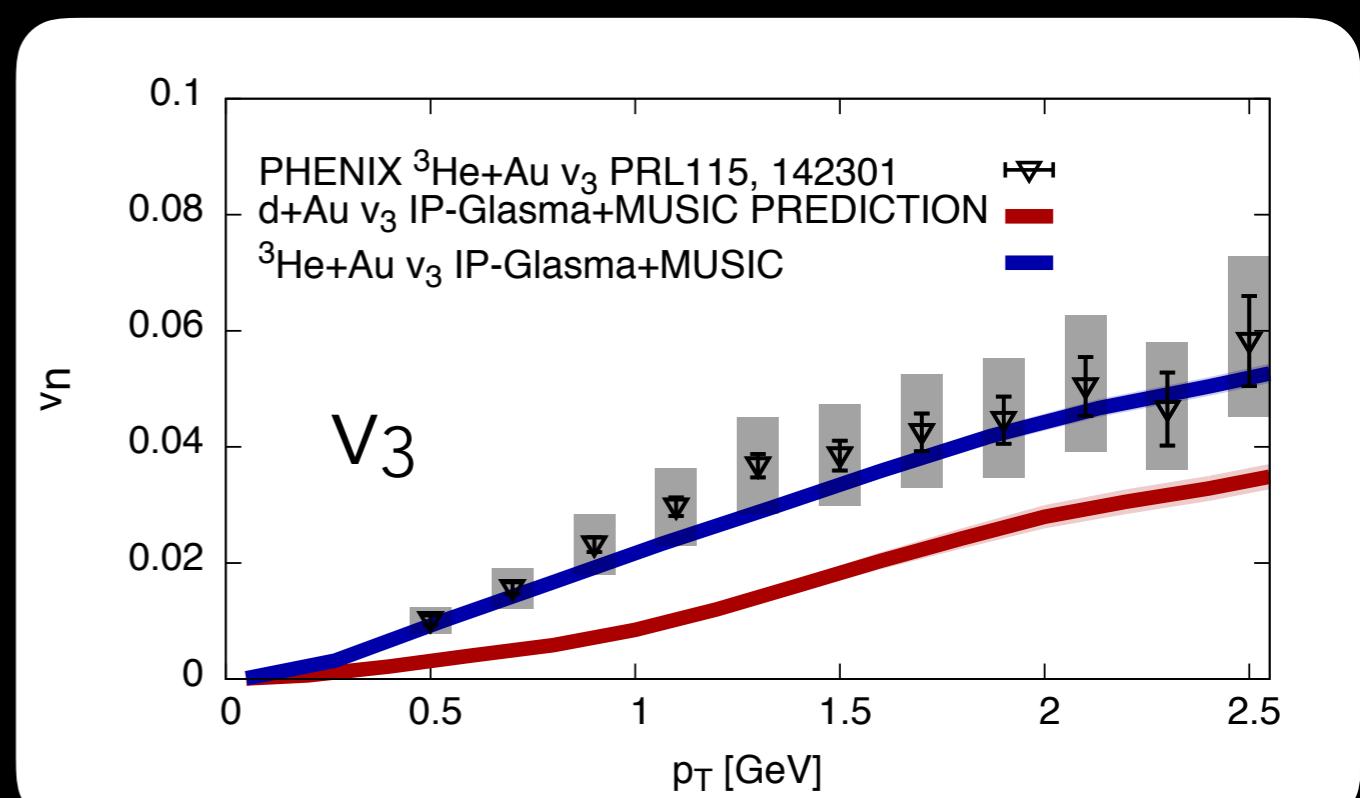
$d+\text{Au}$: PHENIX Collaboration, Phys. Rev. Lett. 114 (2015) 192301
 ${}^3\text{He}+\text{Au}$: PHENIX Collaboration, Phys. Rev. Lett. 115, 142301 (2015)
P. Romatschke, Eur. Phys. J. C 75 (2015) 305

d+Au ^3He +Au Hydro Predictions

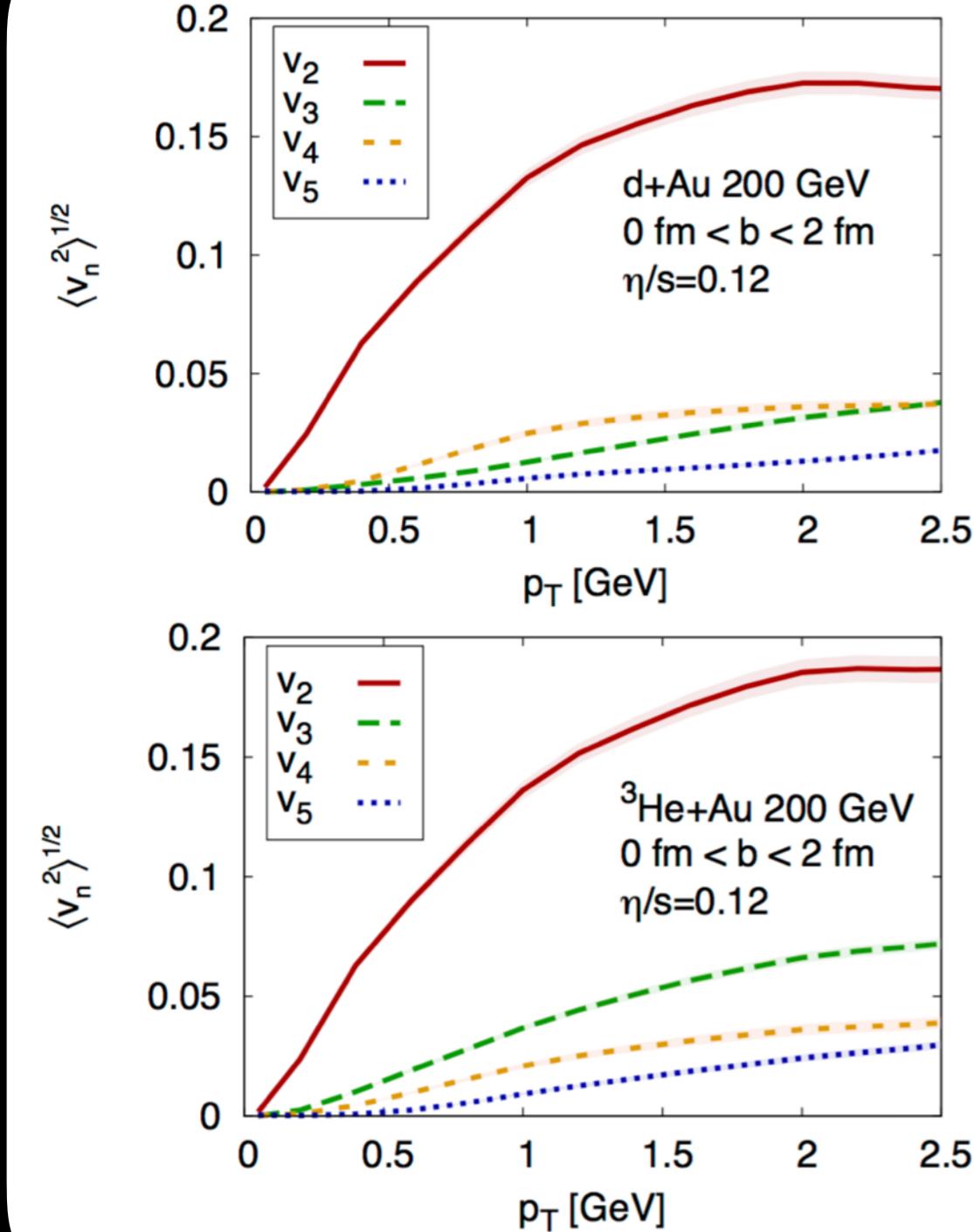


Left: Initial prediction for $d+\text{Au}$ and $^3\text{He}+\text{Au}$ with $\eta/s=0.12$
Bottom: adjusted calculation with $\eta/s=0.18$

d+Au v_3 is a true prediction
(shown @2015 RHIC&AGS Users' Meeting)

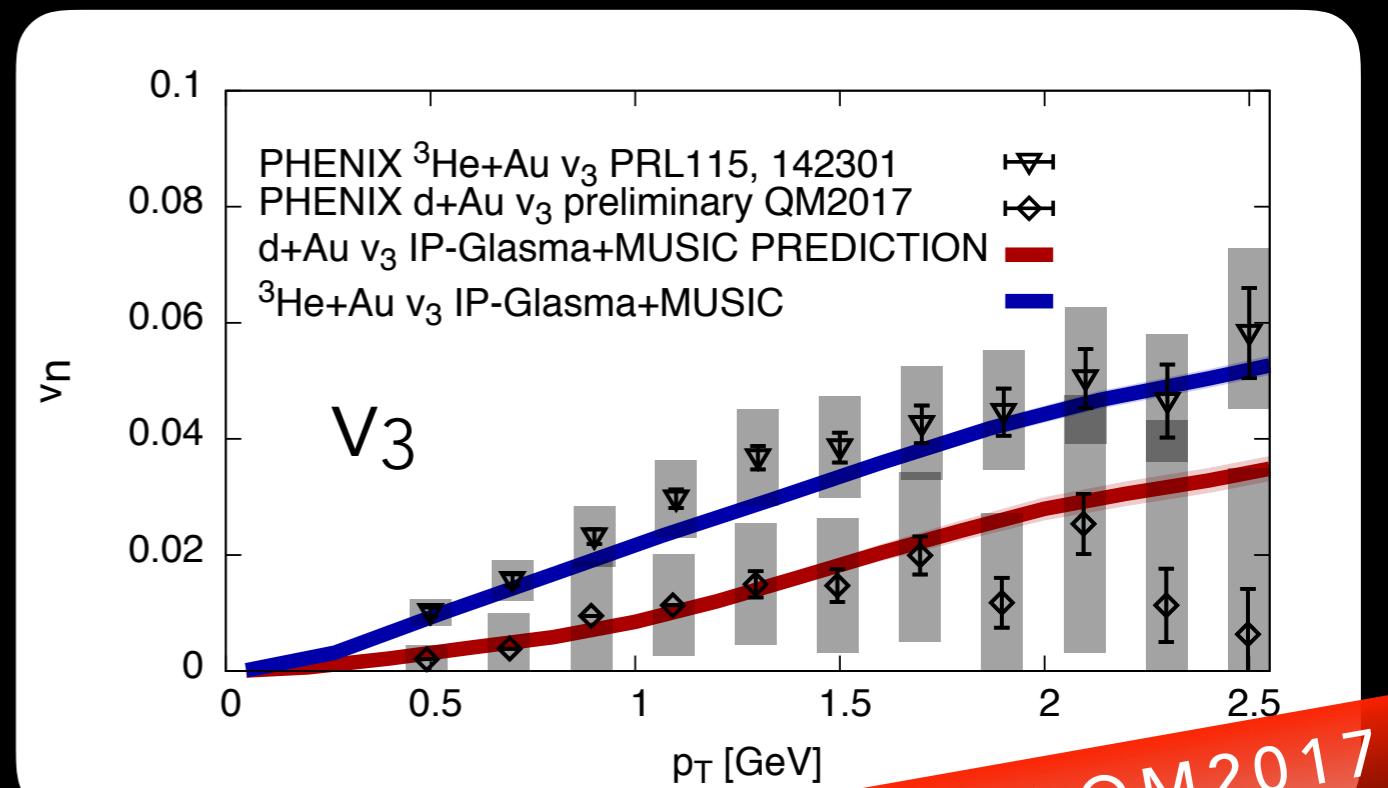


d+Au ^3He +Au Hydro Predictions



Left: Initial prediction for d+Au and $^3\text{He}+\text{Au}$ with $\eta/s=0.12$
Bottom: adjusted calculation with $\eta/s=0.18$

d+Au v_3 is a true prediction
(shown @2015 RHIC&AGS Users' Meeting)



Initial state picture

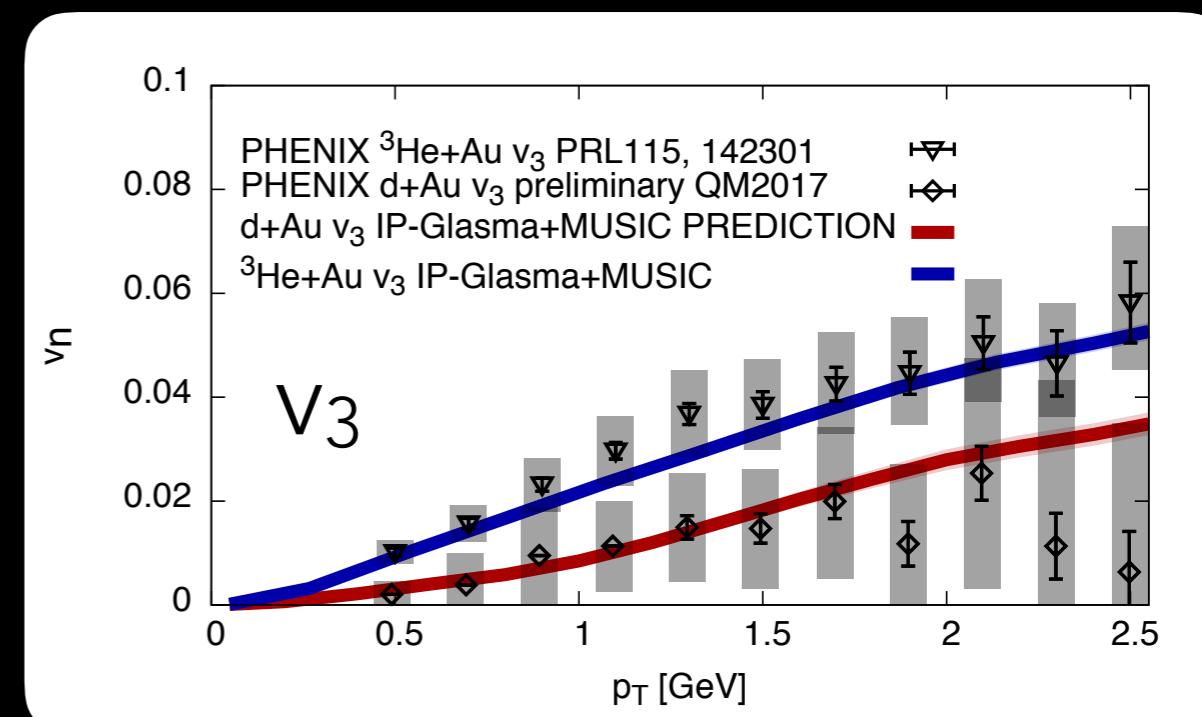
So far there is no initial state calculation comparing different small collision systems

There is no correlation between the harmonics and the initial global eccentricities

B. Schenke, S. Schlichting, R. Venugopalan, Phys. Lett. B747, 76-82 (2015)

L. McLerran, V. Skokov, arXiv:1611.09870

Difference must have a different origin:
Different multiplicities in the 0-5% bin?



Summary

Numerical simulations of effective theories of QCD provide

- The initial state of heavy ion collisions
(Color Glass Condensate)
- The evolution of the produced hot and dense matter
(Hydrodynamics)

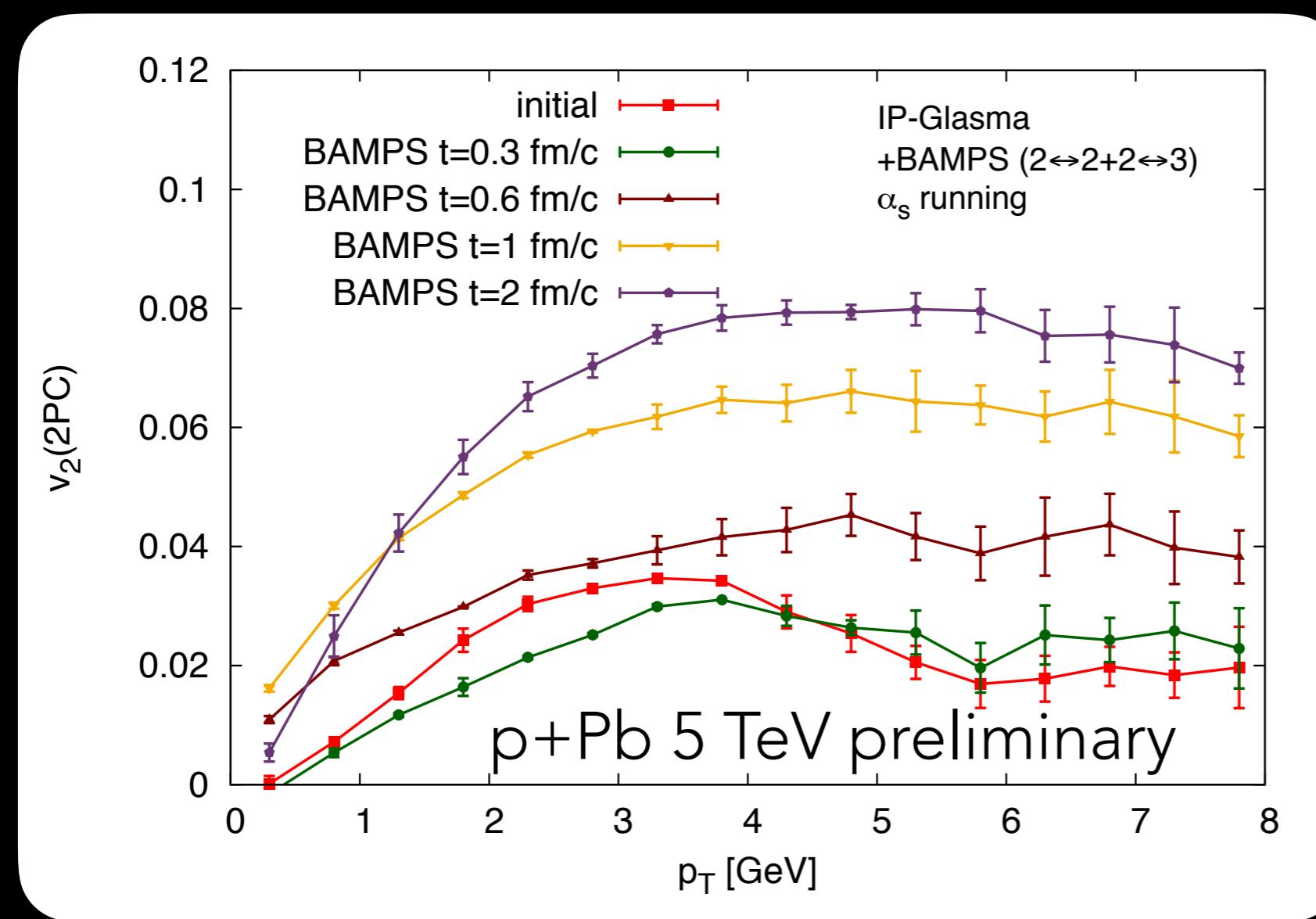
Small systems also well described in the same framework

Different small systems indicate that measured correlations
are sensitive to the initial geometry → final state effect

No question initial state anisotropies exist - do they survive?

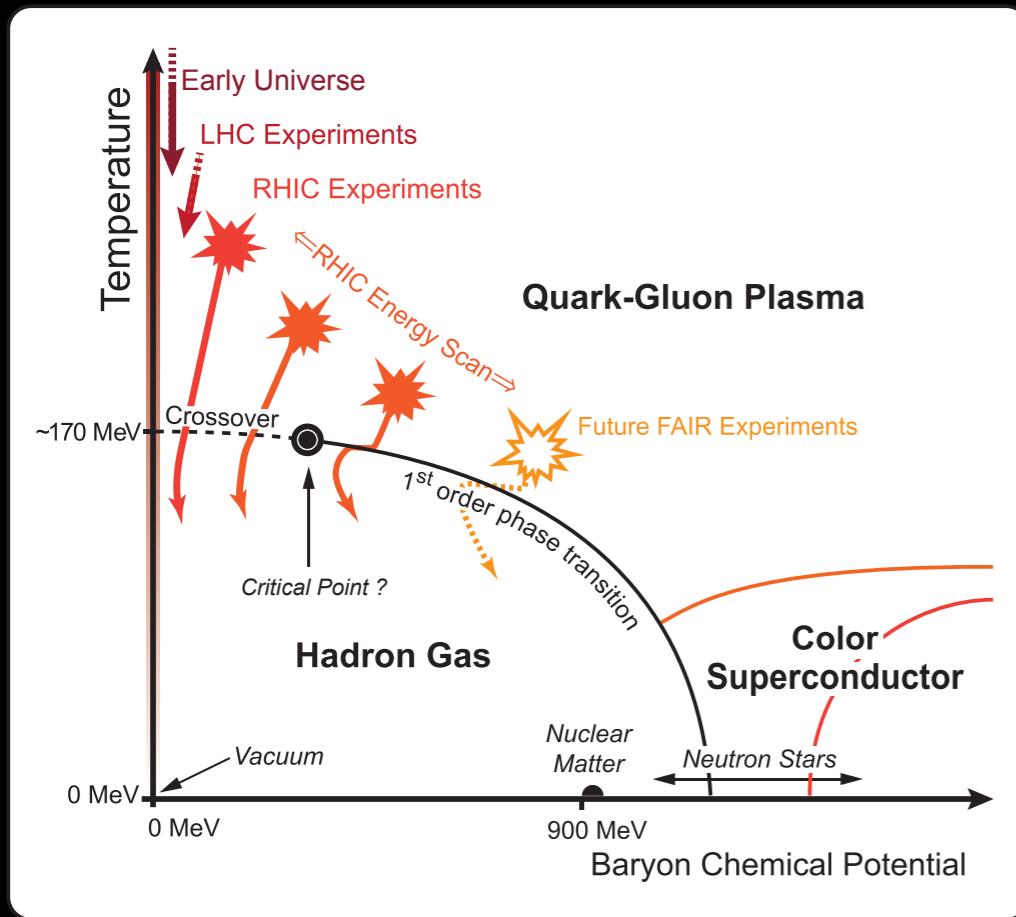
Outlook I: Small systems

For final conclusion on small systems we need theoretical framework that includes both initial and final state interactions:



We compute Wigner functions of gluons from IP-Glasma (includes initial state correlations) and have gluons undergo final state interactions in parton cascade BAMPS

Outlook II: Phase diagram - BES



Our framework will be applied
to reveal critical fluctuations
e.g. in net-baryon distributions

Necessary to pin down existence/
location of QCD critical point

Working on new dynamic initial state for entropy and baryon density, extension of IP-Glasma to 3D, new equation of state with latest lattice input from the HotQCD collaboration, baryon diffusion **with C. Gale, S. Jeon, A. Monnai, J.-F. Paquet, B. Schenke, S. Schlichting, C. Shen**

Outlook III: Hard probes - sPHENIX

Study interaction of high momentum particles with the quark-gluon fluid



Information on different momentum/length scales

Study jet evolution in the medium using Monte Carlo generator MARTINI and hydrodynamic backgrounds

Extend energy loss to Next to Leading Order

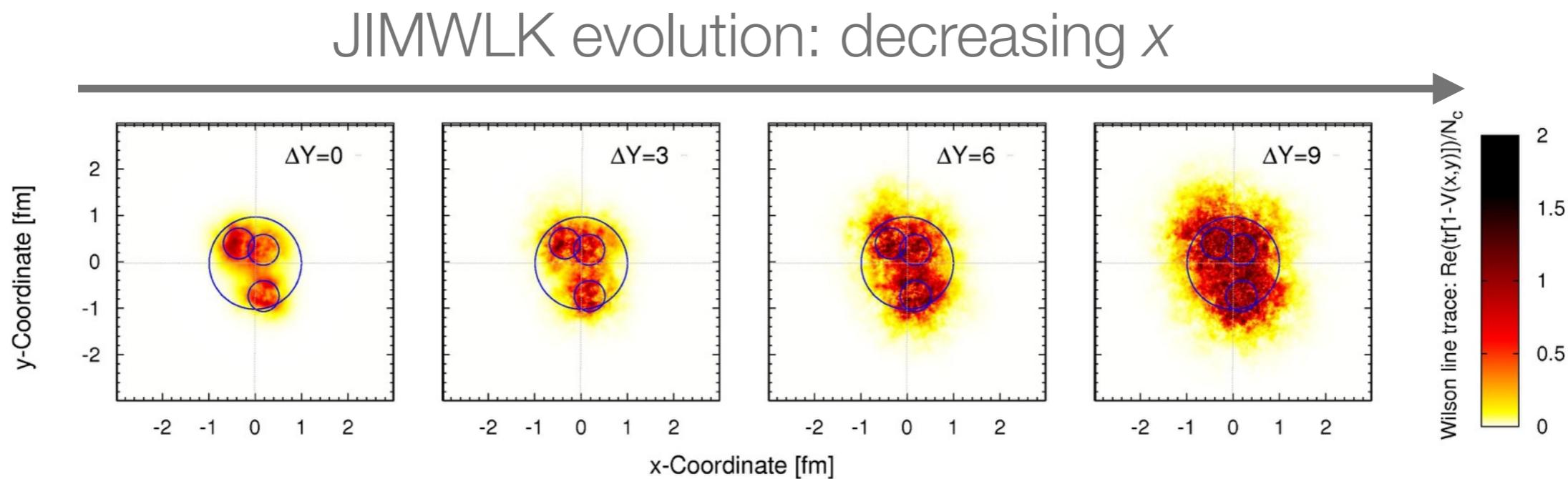
H. Mäntysaari, J.-F. Paquet, B. Schenke, D. Teaney, work in progress

Outlook IV: Electron Ion Collider

Working on calculations relevant to a future EIC:

H. Mäntysaari, B. Schenke, work in progress

- Diffraction - more on proton and nuclear shape and fluctuations
- Small- x evolution of structure functions etc.
- Interesting fundamental questions and input for heavy in program



S. Schlichting, B. Schenke, Phys. Lett. B739, 313-319 (2014)

Even at small x the proton is not a sphere of gluons

Thank you!

- This work is supported by



Office of
Science

- Computations done at the National Energy Research Scientific Computing Center supported by the Office of Science of the U.S. DOE



- Thanks to all my collaborators!